

NASA Technical Memorandum 4773

High-Alpha Handling Qualities Flight Research on the NASA F/A-18 High Alpha Research Vehicle

Keith D. Wichman, Joseph W. Pahle, Catherine Bahm, John B. Davidson,
Barton J. Bacon, Patrick C. Murphy, Aaron J. Ostroff, and Keith D. Hoffler

November 1996



High-Alpha Handling Qualities Flight Research on the NASA F/A-18 High Alpha Research Vehicle

Keith D. Wichman, Joseph W. Pahle, and Catherine Bahm
NASA Dryden Flight Research Center
Edwards, California

John B. Davidson, Barton J. Bacon, Patrick C. Murphy,
and Aaron J. Ostroff
NASA Langley Research Center
Hampton, Virginia

Keith D. Hoffler
ViGYAN, Inc.
Hampton, Virginia



National Aeronautics and
Space Administration

Office of Management

Scientific and Technical
Information Program

1996

HIGH-ALPHA HANDLING QUALITIES FLIGHT RESEARCH ON THE NASA F/A-18 HIGH ALPHA RESEARCH VEHICLE

Keith D. Wichman
Joseph W. Pahle
Catherine Bahm
NASA Dryden Flight Research Center
Edwards, CA

John B. Davidson
Barton J. Bacon
Patrick C. Murphy
Aaron J. Ostroff
NASA Langley Research Center
Hampton, VA

Keith D. Hoffler
ViGYAN, Inc.
Hampton, VA

ABSTRACT

A flight research study of high-angle-of-attack handling qualities has been conducted at the NASA Dryden Flight Research Center using the F/A-18 High Alpha Research Vehicle (HARV). The objectives were to create a high-angle-of-attack handling qualities flight database, develop appropriate research evaluation maneuvers, and evaluate high-angle-of-attack handling qualities guidelines and criteria. Using linear and nonlinear simulations and flight research data, the predictions from each criterion were compared with the pilot ratings and comments. Proposed high-angle-of-attack nonlinear design guidelines and proposed handling qualities criteria and guidelines developed using piloted simulation were considered. Recently formulated time-domain Neal-Smith guidelines were also considered for application to high-angle-of-attack maneuvering. Conventional envelope criteria were evaluated for possible extension to the high-angle-of-attack regime. Additionally, the maneuvers were studied as potential evaluation techniques, including a limited validation of the proposed standard evaluation maneuver set. This paper gives an overview of these research objectives through examples and summarizes result highlights. The maneuver development is described briefly, the criteria evaluation is emphasized with example results given, and a brief discussion of the database form and content is presented.

NOMENCLATURE

Acronyms

ACM	air combat maneuvering
ANSER	actuated nose strakes for enhanced rolling
BFM	basic fighter maneuvers
CAP	control anticipation parameter
CHR	Cooper-Harper rating
HARV	High Alpha Research Vehicle
HUD	head-up display
<i>KEAS</i>	knots equivalent airspeed
LOES	lower-order equivalent system
MATV	Multi-Axis Thrust Vectoring
MDA	McDonnell Douglas Aerospace
PIO	pilot-induced oscillation
RFCS	research flight control system
RMS	root mean square
STEMS	standard evaluation maneuvers set
TVCS	thrust-vectoring control system

Symbols

D	time-domain Neal-Smith acquisition time, sec
k_p	Neal-Smith compensator gain, dB
n/α	ratio of load factor change for each angle-of-attack change, g/rad
T_{lag}	Neal-Smith compensator lag time constant, sec
T_{lead}	Neal-Smith compensator lead time constant, sec
$T_{\theta 2}$	time constant of the lag between flight path and pitch attitude, sec
α	angle of attack, deg
ζ_{sp}	short-period damping ratio

τ_{pilot}	Neal-Smith compensator delay time constant, sec
ω_c	Smith-Geddes critical frequency, rad/sec
ω_{sp}	short-period frequency, rad/sec

INTRODUCTION

Interest in flying qualities in the high-angle-of-attack flight regime has traditionally been limited to departure-resistance characteristics. With the advent of advanced control effectors such as multiaxis thrust vectoring and closed-loop forebody vortex control, this flight regime can now be exploited for enhanced fighter maneuverability and, therefore, tactical advantage. New definitions of desirable handling qualities at high angles of attack must complement this new maneuvering potential in order to effectively use these advanced controllers. Aircraft designers and testing agents must have flight-validated guidelines, evaluation maneuvers, and flight test techniques to define handling qualities at high angles of attack and to facilitate the meaningful evaluation of these aircraft.

Advanced flight research within the high-angle-of-attack flight regime has been conducted at the NASA Dryden Flight Research Center (NASA Dryden) as part of the High-Alpha Technology Program. For the purposes of this research, “high angles of attack” are angles ranging from 30° to 70°. This research was conducted using the NASA F/A-18 High Alpha Research Vehicle (HARV). One facet of this project was to improve understanding of high-angle-of-attack handling qualities. The research objectives were to create a high-angle-of-attack handling qualities flight database, develop appropriate research evaluation maneuvers, and evaluate high-angle-of-attack handling qualities guidelines and criteria.

A few aircraft have been developed and tested using such advanced control effectors. These aircraft were oriented primarily towards operational utility of the control effectors rather than general research of the flight regime. The X-31A flight program featured multiaxis thrust vectoring and primarily investigated enhanced fighter maneuverability and the tactical utility of vectoring. A limited study of high-angle-of-attack handling qualities was conducted at the end of the program using maneuvers similar to those used in the HARV research program.¹ The resulting data will provide an important overlap with HARV research to validate results for more than one airframe. A significant limitation in the scope of the X-31A handling qualities was the lack of control system variations.

The F-16 Multi-Axis Thrust Vectoring (MATV) aircraft high-angles-of-attack handling qualities were evaluated.² Some evaluation maneuvers developed by the HARV program were used. Because of the MATV program goal of rapid evaluation and demonstration of an operational-type thrust-vectoring system, the primary emphasis was to evaluate the dynamics of the aircraft configuration rather than to conduct specific research on high-angle-of-attack handling qualities. As with the X-31A program, few variations in aircraft dynamics were evaluated.

This paper gives an overview of these HARV handling qualities research objectives through examples and summarizes result highlights. The maneuver development is described briefly, the

criteria evaluation is covered at length with example results given, and a brief discussion of the database form and content is presented.

DESCRIPTION OF FACILITIES

The facilities required to conduct the handling qualities research included the HARV aircraft, nonlinear six-degrees-of-freedom simulations (piloted and batch), and validated linear models. These facilities are described in the following sections.

High Alpha Research Vehicle Aircraft

The HARV aircraft, equipped with a reconfigurable research flight control system (RFCS), was an excellent facility for high-angle-of-attack investigation (fig. 1). The aircraft features included a multiaxis thrust-vectoring control system (TVCS) and, for the final phase of the program, forebody vortex control using the actuated nose strakes for enhanced rolling (ANSER) system integrated into the stable high-angle-of-attack F/A-18 airframe. The RFCS provided the capability to examine multiple control law designs and their variants without compromising the safety of the pilot or aircraft. This research computer was designed to provide a Class B (mission critical but not safety critical) control environment that, by definition, ensures safe reversion back to the standard F/A-18 configuration if a failure were detected or if the pilot believed a danger existed. The inherent spin resistance of the F/A-18 airframe and the spin recovery chute added to the suitability of



EC96 43479-5

Figure 1. HARV aircraft.

the test bed for safe high-angle-of-attack flight research. Additionally, the many aerodynamic control surfaces and the added thrust vectoring and forebody strakes provided significant variety in control power usage. A more comprehensive description and extensive references of the HARV research and facility is given by Bowers.³

An undesirable result of adding all of this hardware to the aircraft exists. The dramatic change in weight and inertias introduced by the TVCS and related systems resulted in a significant change in the handling qualities of the HARV under the control of the unmodified F/A-18 flight control system. The added weight was primarily at the extreme aft and extreme forward aircraft positions, essentially producing a flying “dumbbell.” In-flight refueling using the basic flight control system was an extremely difficult task with very strong longitudinal pilot-induced oscillation (PIO) tendencies. Figure 2 shows time-history data of one such refueling attempt. A potential effect of this tendency was to cause the research control law designers to begin with a handicap in pitch dynamics. Each longitudinal research control law design exhibited at least some tendency to be sensitive or oscillatory in the pitch axis, with the common result of less than desirable pitch-tracking handling qualities.

Simulation Facilities

A broad range of ground-test and simulation facilities were used concurrently during the HARV program. The primary piloted simulation used in the development of performance guidelines and handling qualities evaluations was the fixed-base, 40-ft dome differential maneuvering simulator at the NASA Langley Research Center. The differential maneuvering simulator was also

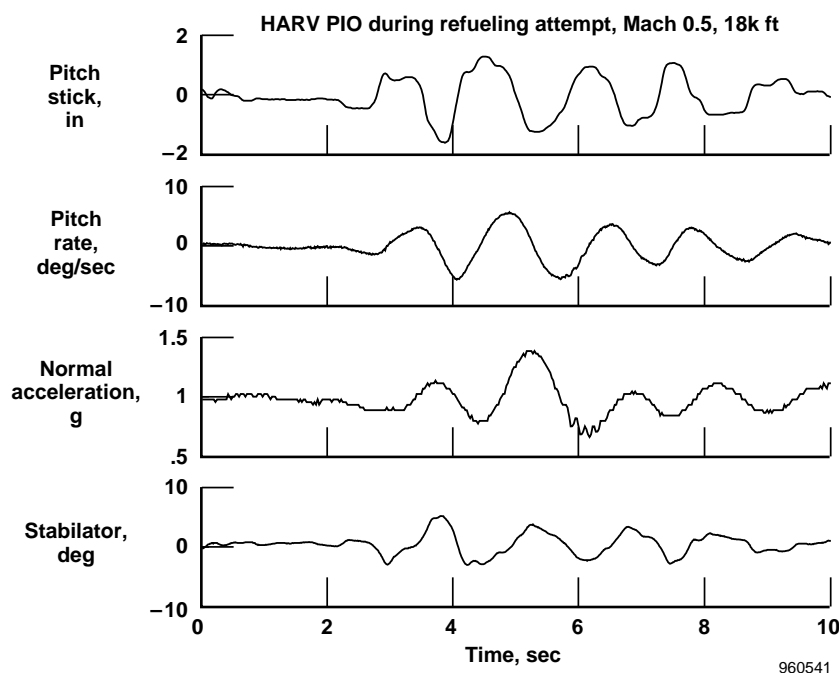


Figure 2. Time history of in-flight refueling PIO.

used in the control law design process and flight maneuver development.⁴ The piloted simulation at NASA Dryden was limited to forward visuals only, but could be linked with an all-software, hardware-in-the-loop, or iron-bird capability. The NASA Dryden simulation was used for flight planning, engineering, and software development, and was the primary site for software and hardware verification and validation testing. A configuration-controlled batch simulation, common to both sites, was used as a benchmark from which to compare other dissimilar simulations.

Linear Models

Validating that the linear models used extensively for evaluation of the handling qualities criteria represented adequate reflections of the observed HARV flight dynamics was important. The models compared quite favorably with the nonlinear simulation in both the frequency and time domains (figs. 3 and 4). This nonlinear simulation has had a long history of accurately modeling the F/A-18 and HARV flight dynamics. These comparisons were made in both the time and frequency domain for relatively small input magnitudes. As input size increases, the number of system nonlinearities increases and the confidence in the models decreases. For most of the cases researched, this small input assumption is appropriate (fine and not-so-fine tracking). For gross-acquisition analysis, these linear assumptions, and therefore any linear analysis technique results, become suspect. Throughout the HARV program, the nonlinear simulation and the linear models proved representative of the actual aircraft system dynamics, given the assumptions just discussed. Through this and additional experience with these models, great confidence in their validity has been developed.

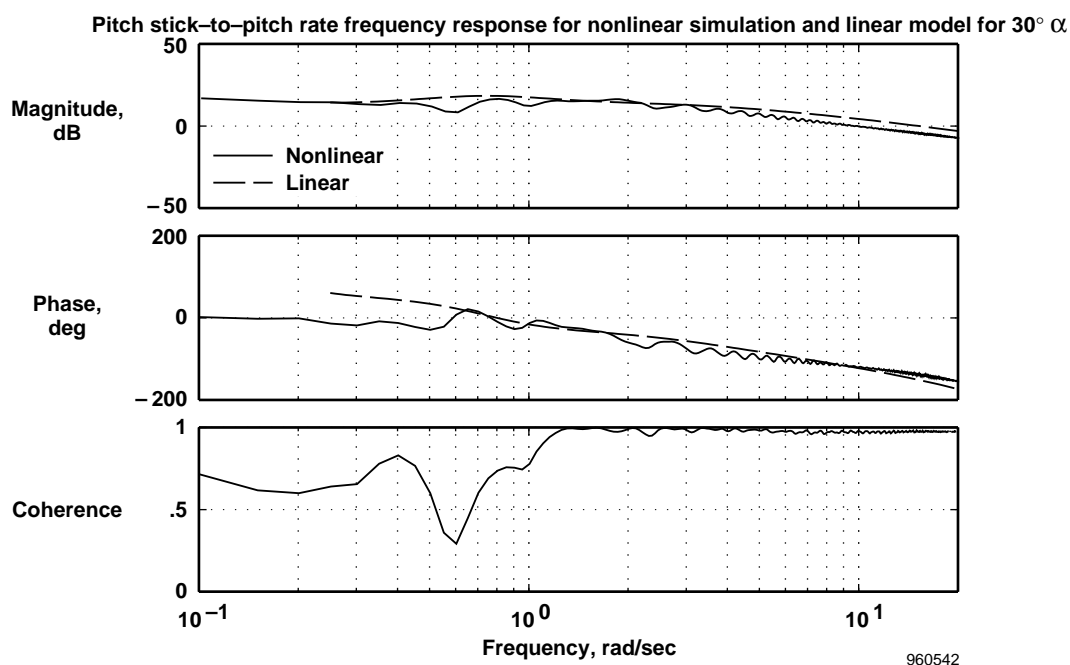


Figure 3. Frequency-domain linear model validation example.

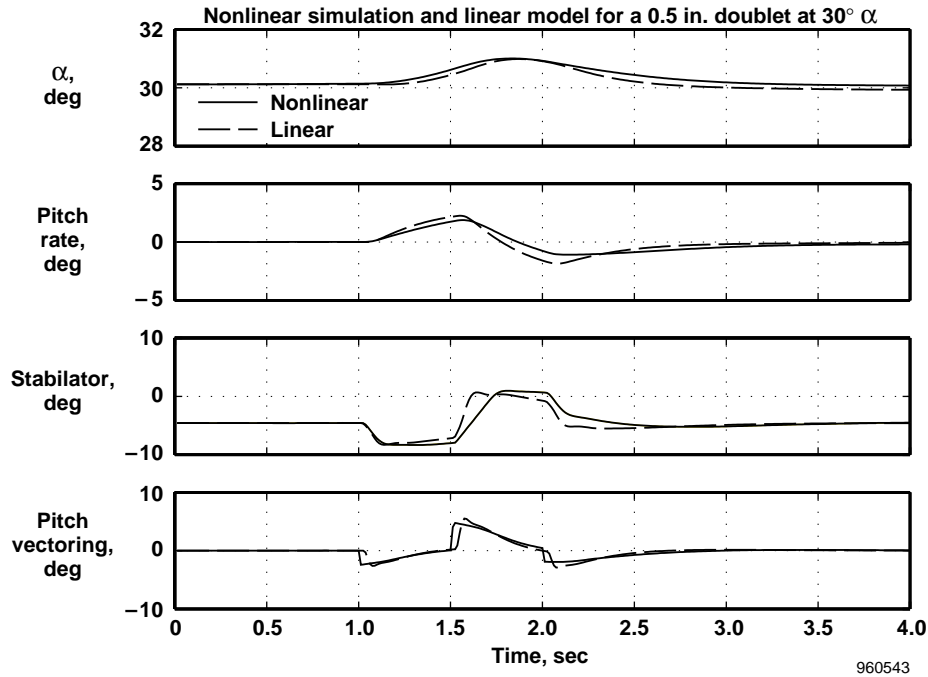


Figure 4. Time-domain linear model validation example.

DESCRIPTION OF EXPERIMENT

The research experiment conducted using the HARV aircraft resulted in a comprehensive yet limited handling qualities flight database for the high-angle-of-attack flight regime where none previously existed, and important insights can be derived from it. The study evaluated longitudinal and lateral-directional gross-acquisition and tracking handling qualities from 30° to 60° angle of attack (α), parametric gross acquisition, open-loop performance effects, basic fighter maneuvering, and air combat maneuvering (ACM). Numerous control law configurations and advanced control effectors, including the forebody strakes and thrust vectoring, were used to vary available control power and the closed-loop dynamics. The handling qualities of these configuration variations ranged from good tracking and gross-acquisition characteristics to very poor handling qualities, including divergent PIOs. The database was created primarily using two project pilots and several guest pilots. An extensive simulation database using fixed-base dome and some motion-based simulators was created for comparison with flight results. Head-up display (HUD) video and pilot comments were cataloged with the flight time-history data.

In spite of its significance, the HARV handling qualities flight database was limited and problematic in many respects. These limitations resulted from the fact that the HARV project was not dedicated exclusively to handling qualities research but to high- α flight in general, embracing multiple disciplines. This necessity to share the facility and the large amount of valuable flight time required for the handling qualities maneuvers dictated a “first look” approach to this research. This approach led to a broad but shallow database that was compiled over several years, often with large time gaps separating research points. These time gaps disrupted the continuity and consistency of

both the maneuver quality and pilot evaluation. Therefore, the resulting database cannot be considered statistically significant.

A description of the various research control laws developed and tested by the HARV project team is given by Pahle.⁵ Except where noted, this paper will only be concerned with the distinctions among the control laws in order to present the breadth of the database and to illustrate examples of the performance of the various candidate handling qualities criteria and guidelines.

The three major sections of this paper that follow address the handling qualities research objectives of the HARV project. These objectives were to create a high- α handling qualities flight database, develop appropriate research evaluation maneuvers, and evaluate high- α handling qualities guidelines and criteria. The greatest emphasis will be given to the guidelines and criteria evaluation; however, brief overviews of the database and maneuver development objectives are included. The test conduct was separated into the following distinct efforts:

- Flight data acquisition: Conduct handling qualities flight maneuvers and acquire flight data, HUD video, pilot ratings, and comments for the control law variations made possible by other research objectives. The resulting database was the truth model.
- Handling qualities criteria predictions: Perform analysis of simulation data using various handling qualities criteria to generate the predictions for the handling qualities of each control law configuration flown.
- Evaluation and modification: Compare the criteria predictions with the flight results evaluating the applicability and accuracy of each criteria and attempt to modify them if necessary.

HIGH-ANGLE-OF-ATTACK EVALUATION MANEUVERS

In order to evaluate high- α handling qualities, developing and flight-validating appropriate maneuvers was necessary. Because of the unconventional maneuvering possible in this flight regime with the advanced controllers mentioned, conventional evaluation maneuvers for low angles of attack needed to be adapted and new maneuvers needed to be developed. Ground-based simulations were used extensively to develop and refine these maneuvers.^{6,7} Some in-flight trial and error was required to further refine the maneuvers. Most noteworthy of these maneuvers were the high- α tracking and acquisition maneuvers (fig. 5). These maneuvers were very effective at isolating the longitudinal from the lateral-directional axes and gross-acquisition from fine-tracking performance. These maneuvers were conducted at discrete angles of attack of 30°, 45°, and 60°. The maneuvers were highly repeatable and gave good discrimination of both good and poor handling qualities.

Many other maneuvers were developed or refined as discussed in the next section of this paper. Open-loop performance, parametric closed-loop (such as g , α , pitch attitude-angle, and bank-angle captures), targeted closed-loop (tracking and acquisition), basic fighter maneuvers (BFM), and ACM make up the general classes of maneuvers developed and refined by the HARV team for high- α evaluation. All of these maneuvers aided in the evaluation of various guidelines and criteria as discussed in the next section.

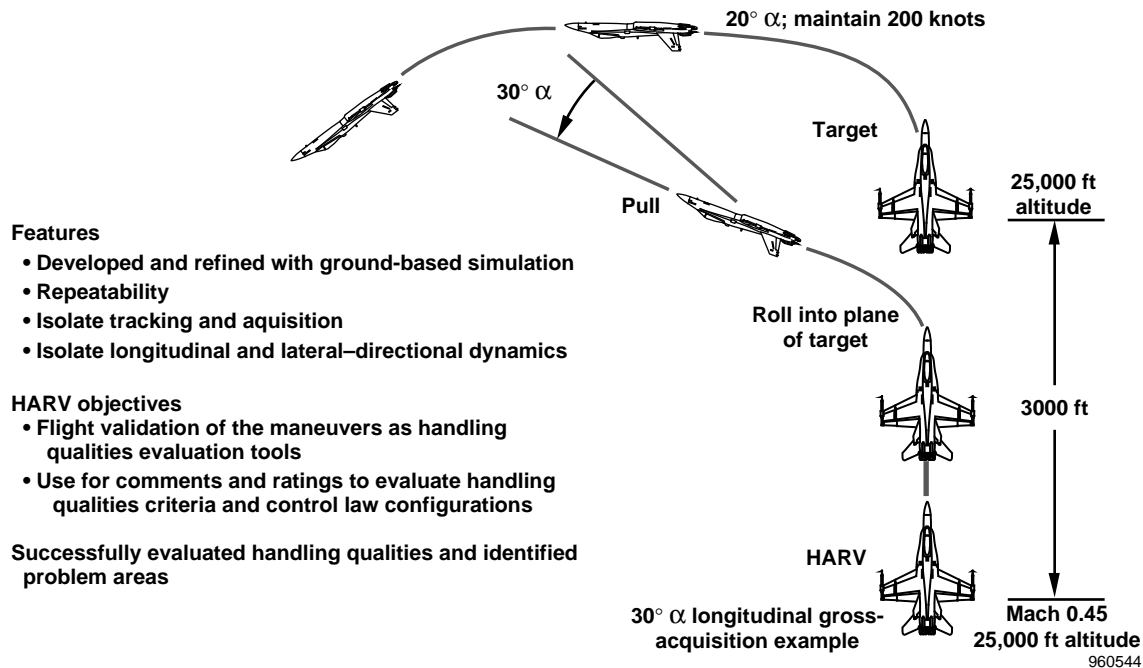


Figure 5. High-angle-of-attack tracking and acquisition maneuvers.

Maneuver Pyramid

The handling qualities maneuvers were examined as a group as a potential evaluation technique. These maneuvers were organized into a “maneuver pyramid” (fig. 6) where maneuvers useful to engineering design could be progressively linked with maneuvers having operational significance to a combat pilot. Maneuvers towards the bottom of the pyramid were relatively large in number, repeatable, easy to fly, well-suited for simulation evaluation, and gave results that the controls designer could easily translate to design parameters. Maneuvers near the top of the pyramid were comparatively small in number, costly to fly, less repeatable, less suited for simulation evaluation, and had less direct translation to design parameters than the other maneuvers. These maneuvers were, however, significantly more representative of the operational tasks that the control law and aircraft system were designed to enhance than the maneuvers towards the bottom of the pyramid.

This maneuver pyramid can be described by the following progression. Open-loop performance maneuvers were followed by parametric closed-loop maneuvers such as α or pitch-attitude captures. These parametric closed-loop maneuvers were followed by target acquisition and tracking maneuvers. Finally, a small number of BFM such as break turns and “J turns” against targets were employed, followed by an even smaller number of ACM engagements. These engagements were one-against-one, unstructured, simulated combat engagements, unlike the other maneuvers, which were predefined and highly structured. The purpose of the ACM (and to some extent the BFM) was to uncover any characteristics or latent deficiencies that might only be detected by such free-form maneuvering. An attempt was made to identify a link throughout this maneuver progression of “good” or “bad” performance and handling qualities and to relate the specific deficiency or

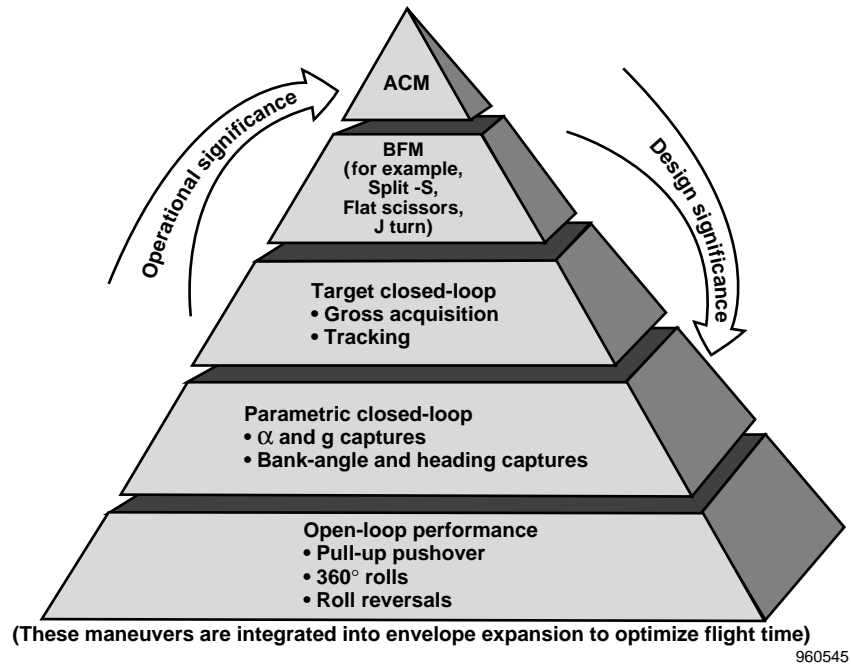


Figure 6. Maneuver pyramid for high-angle-of-attack handling qualities evaluation.

enhancement to specific elements of control system design. The effectiveness of this pyramid for uncovering control law deficiencies early in the development process and linking these with parameters the designer could readily use was evaluated during the program.

Using this pyramid, figure 7 shows pilot ratings from flight arranged as a function of maneuver and flight condition for the Version 27 control law. This configuration demonstrated pitch bobbling and sensitivity problems during the target tracking and acquisition maneuvers. The implication can be drawn from this figure and the associated pilot comments that a necessary but not sufficient relation of the low-level engineering maneuvers with high-level operational maneuvers exists. Poor performance or handling qualities indications during the engineering-type maneuvers typically carried through to deficiencies in the operationally significant maneuvers. However, poor performance or handling qualities uncovered during the operational-type maneuvers were not necessarily indicated clearly by the results of the low-level maneuvers.

Standard Evaluation Maneuvers Set

The standard evaluation maneuvers set (STEMS) of 20 maneuvers was developed by McDonnell Douglas Aerospace (MDA) (St. Louis, Missouri) under contract to the U.S. Air Force.⁷ These maneuvers have been candidates for inclusion in the revision of MIL-STD-1797 as handling qualities demonstration maneuvers. The STEMS was intended to provide a “mission-oriented” evaluation of aircraft handling qualities as opposed to a parametric criteria-based specification. The HARV facility was used in support of the MIL-STD-1797 revision to validate 17 of the maneuvers in the set (table 1) in terms of flyability and effectiveness at evaluating flying qualities, particularly at high angles of attack. The tests were conducted using two HARV project pilots and two flight

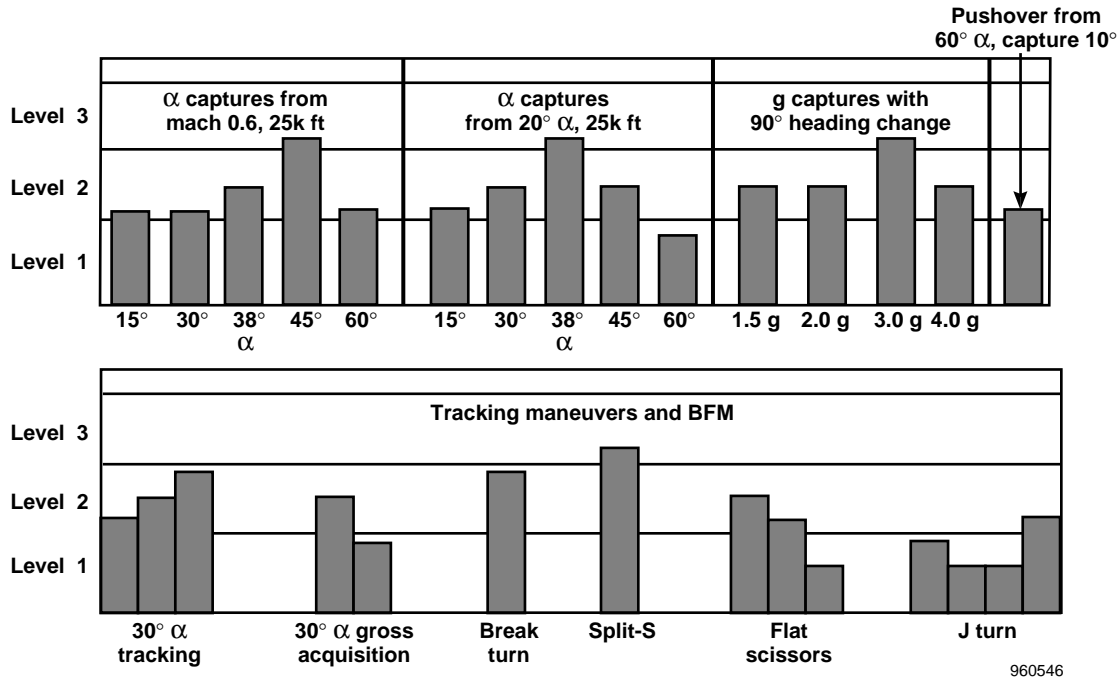


Figure 7. Longitudinal closed-loop pilot ratings for Version 27 control law.

control systems, including various thrust-vectoring and forebody strakes combinations. The pilots evaluated each maneuver based on definition, target setup, difficulty, repeatability, and similarity to an operational task and were asked to offer improvement recommendations. Results favorably indicated that such a maneuver set could be effectively used to demonstrate handling qualities, uncover operational deficiencies, and represent some elements of operational tasks.⁸

Table 1. STEMS maneuver sequence flown on the HARV aircraft.

STEM 6	Maximum pitch pull
STEM 16	1-g stabilized pushover
STEM 14	Minimum speed for 80° pitch
STEM 17	J turn
STEM 15	Minimum time 180° heading change
STEM 9	Pitch rate reserve
STEM 13	High- α roll and capture
STEM 12	High- α roll reversal
STEM 5	Rolling defense
STEM 7	Noseup pitch angle capture (medium)

Table 1. Concluded.

STEM 7	Noseup pitch angle capture (low)
STEM 10	High- α longitudinal gross acquisition
STEM 3	High- α lateral gross acquisition
STEM 1	Tracking during high- α sweep
STEM 2	High- α longitudinal and lateral tracking
STEM 4	Dual attack
STEM 8	Crossing target acquisition and tracking
STEM 11	Sharkenhausen

Stepping-Target Simulation Task

A longitudinal PIO was encountered during fine tracking during the flight test of the NASA-1A control law. The PIO was not accurately predicted by ground-based simulation prior to the 1994 flight test of the control law. After the 1994 flight test evaluation, a piloted simulation test technique was developed to reproduce the PIO tendencies seen in flight. The technique was then used to test iterations of the control law redesign, ANSER, in an attempt to eliminate the PIO. A second flight test phase was made with the ANSER control law in 1995 and 1996. The PIO tendencies were nearly eliminated in flight with the modified control laws. Hoffler discusses the original and modified tracking task, or “stepping-target” task, simulation techniques in detail.⁹

The goal of the stepping-target tracking task technique was to increase pilot gain during simulation evaluations. The original tracking tasks were changed in two ways: pilot requirements were changed from tracking criteria and Cooper-Harper ratings to the use of a pseudogun model to “kill” the target, and the target trajectory was modified from a steady turn to a steady turn with discrete steps superimposed on the flight path (the “stepping target”). The prerecorded targets used for earlier evaluations were utilized with the stepping target superimposed on their trajectory. The target made discrete steps along the normal axis of the tracking airplane. From the pilot’s point of view, the target made random discrete steps along the vertical axis of the HUD. The steps occurred at bounded random time intervals and had bounded random amplitudes. The piloting task was changed from requiring time on target to requiring the pilot to attempt to achieve a “gun kill” against the target. Kills required 75 hits and the pilot was given 100 rounds; hence, 75 percent of the rounds available were required to kill the target. The stepping-target tracking task was shown to be an effective simulation technique for reducing PIO potential during control system design.⁹

HIGH-ANGLE-OF-ATTACK CRITERIA EVALUATED

Another major objective of the HARV handling qualities research was the evaluation of techniques for predicting and specifying high- α handling qualities. Using linear and nonlinear simulations and flight research data, the results from each analysis technique were compared with the pilot ratings and comments from the flight evaluations.

These design guidelines and criteria fell under the general subheadings of open-loop performance guidelines, linear techniques, and techniques compensating for system nonlinearities. Considered in this study were proposed high- α nonlinear design guidelines and proposed handling qualities criteria and guidelines developed using piloted simulation. Recently formulated time-domain Neal-Smith guidelines were also considered for application to high- α maneuvering. Conventional envelope criteria such as bandwidth, Neal-Smith, Smith-Geddes, and lower-order equivalent systems-based guidelines found in MIL-STD-1797¹⁰ were evaluated for possible extension to the high- α regime. The following sections briefly introduce these criteria and guidelines and present example results. Table 2 shows a very brief summary of the general handling qualities of the control law variations that are referenced throughout the paper.

Table 2. HARV control law version summary.

NASA-0	NASA Dryden modified MDA design (thrust vectoring only).
Version 26	Apparently good pitch tracking; poor acquisition predictability. Lateral axis inertial coupling and wind-axis bank-angle overshoot deficiencies.
Version 27	Very bad pitch tracking (bobble, PIO tendency) but good pitch acquisition characteristics. Good lateral-directional qualities.
Version 28	Good pitch tracking and acquisition qualities. Same good lateral handling qualities as Version 27.
NASA-1	NASA Langley design (thrust vectoring and/or forebody strakes)
NASA-1A	Vectoring only, risk reduction for ANSER control laws. Severe pitch PIO during tracking and related difficulties with acquisition. Lateral handling was difficult to assess because of pitch PIO but generally good.
ANSER	Vectoring and strakes. Pitch control law redesigned and included three dial-a-gain pitch sensitivity options. Majority of pitch PIO from NASA-1A eliminated but some sensitivity while tracking remained. Good lateral handling qualities.

Figure 8 shows a summary of the $30^\circ \alpha$ longitudinal tracking handling qualities for the control law versions evaluated. This summary will serve as a guide to the example criteria comparison results that follow. Most noteworthy is the NASA-0 control law version series (Versions 26, 27, and 28), where the tracking characteristics went from Level 1–2 to Level 2–3 and back to the

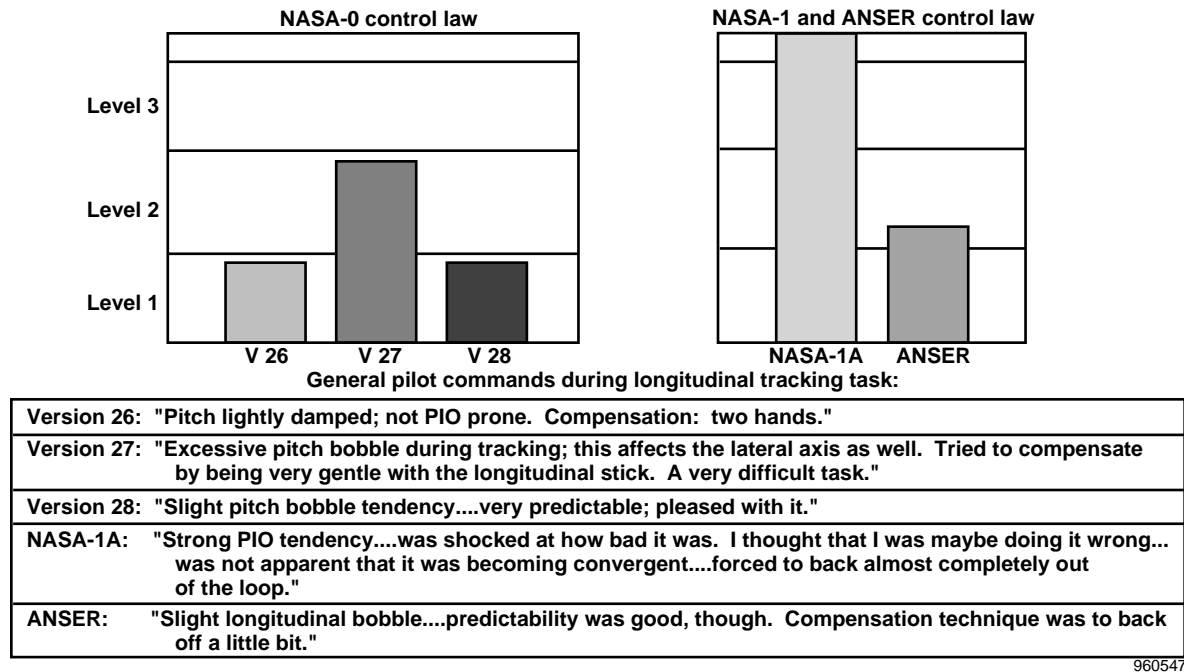


Figure 8. Summary of $30^\circ \alpha$ longitudinal tracking characteristics for tested control laws.

Level 1–2 boundaries, respectively. The pilot comments were considered more significant than the pilot ratings. The comments indicate a definite problem with pitch sensitivity introduced with Version 27 and subsequent improvement in Version 28 to a level somewhat better than that of both previous versions. This known and discernible version history was a valuable resource for evaluating the ability of the various longitudinal criteria to predict the same trends and levels. (It must be noted that there were very few pitch-tracking points flown using Version 26. As will be shown, poor handling qualities were typically predicted by the various criteria for this version, especially for high g levels. Little flight data exist to adequately validate or invalidate these predictions for Version 26. The data for this version are retained in the following examples for comparison of the predictions among the various criteria.) The other longitudinal control law variations flown were the NASA-1A and ANSER control laws. These variations provided a severe pitch sensitivity example with PIO susceptibility and the subsequent successful redesign, respectively.

Open-Loop Performance Guidelines

A set of nonlinear design guidelines for poststall flight did not exist when the HARV thrust-vectoring and control law design began. A set of guidelines was developed at the outset of this program and iterated upon during the design process.^{4,6} The initial set of open-loop performance guidelines is listed below:

- Maximum pitch rate from 1- g and loaded conditions.
- Maximum pitch acceleration from 1- g and loaded conditions.

- Maximum roll rate through 90° bank-angle change from 1-g and loaded conditions.
- Time through 90° bank-angle change.
- Coupling criteria (for example, maximum α and angle-of-sideslip excursions during rolls).

With these guidelines, pitch and yaw acceleration requirements for the thrust-vectoring system could be determined, and goals were set for the control law designs. Details about these guidelines are given by Hoffler.⁶

Overall results using these guidelines indicated that these guidelines worked well for the HARV and appear to be a good start for any poststall-capable airplane. Two significant lessons were learned about the use of these guidelines through ground-based simulation and flight test of the HARV airplane. In the longitudinal axis, the pitch-rate requirements for maneuvers initiated from low angles of attack were too high for the HARV to achieve while maintaining good handling qualities. In the lateral-directional axis, another guideline, the bank-angle overshoot criterion, was developed to make gross-acquisition maneuvers predictable (fig. 9). Figure 9 shows the region meeting the criterion (shaded area) as a function of α for simulation results of three lateral-directional modes of the ANSER control law. This example displays the differences various control effector combinations exhibited with respect to this design guideline. The bank-angle overshoot criterion is also described by Hoffler.⁶ This criterion essentially requires a consistent amount of bank-angle overshoot for angles of attack greater than 25° and dictates that the overshoot be “small.” Observations of pilot performance led to the criterion. It was determined that when a tradeoff between bank-angle overshoot and rate was required, bank-angle overshoot should take precedence. This priority results from the fact that “getting there fast” is only part of the desired outcome. Stopping on the target rather than badly overshooting it or oscillating around it can often make up the difference in time to acquire the target.

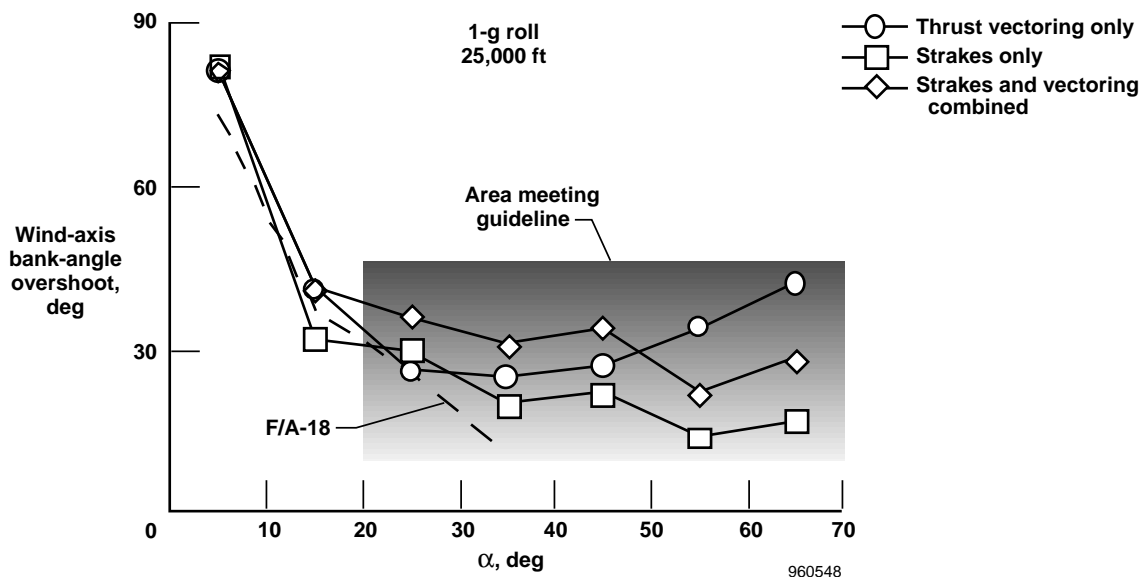


Figure 9. Open-loop performance design guideline: wind-axis bank-angle overshoot from reversal after 90° of wind-axis bank-angle change.

Linear Analysis Techniques

Most conventional handling qualities criteria are formulated with assumptions of linearity. These assumptions are typically appropriate for conventional aircraft and maneuvers. Several linear criteria were evaluated to determine if these linear assumptions could also be appropriate for maneuvering in the high- α regime.

Proposed High-Angle-of-Attack Criteria and Guidelines

High- α handling qualities design guidelines, developed by MDA, were formulated in terms of modal parameters as well as frequency-domain Bode response envelopes.¹¹ These guidelines specify handling qualities boundaries for 30° , 45° , and 60° α ; longitudinal and lateral axes; and tracking and gross acquisition. A limited evaluation of these guidelines was performed using the HARV database. Because these guidelines are restricted by the International Traffic in Arms Regulations, all figures have been sanitized by removing the scales.

McDonnell Douglas Aerospace–Proposed High-Angle-of-Attack Handling Qualities Guidelines: Modal Guidelines

The modal formulation of these criteria require lower-order equivalent system (LOES) transfer function representations of the full-order dynamics. Longitudinal LOES matches could only be determined for the pitch stick-to- α transfer function at high angles of attack. The pitch rate-to-pilot stick and normal acceleration-to-pilot stick transfer functions contain terms dependent upon the load factor for each α change, n/α which becomes essentially 0 g/rad at high α . Figure 10 shows the LOES formulation for the pilot stick-to- α transfer function matched the full-order system quite

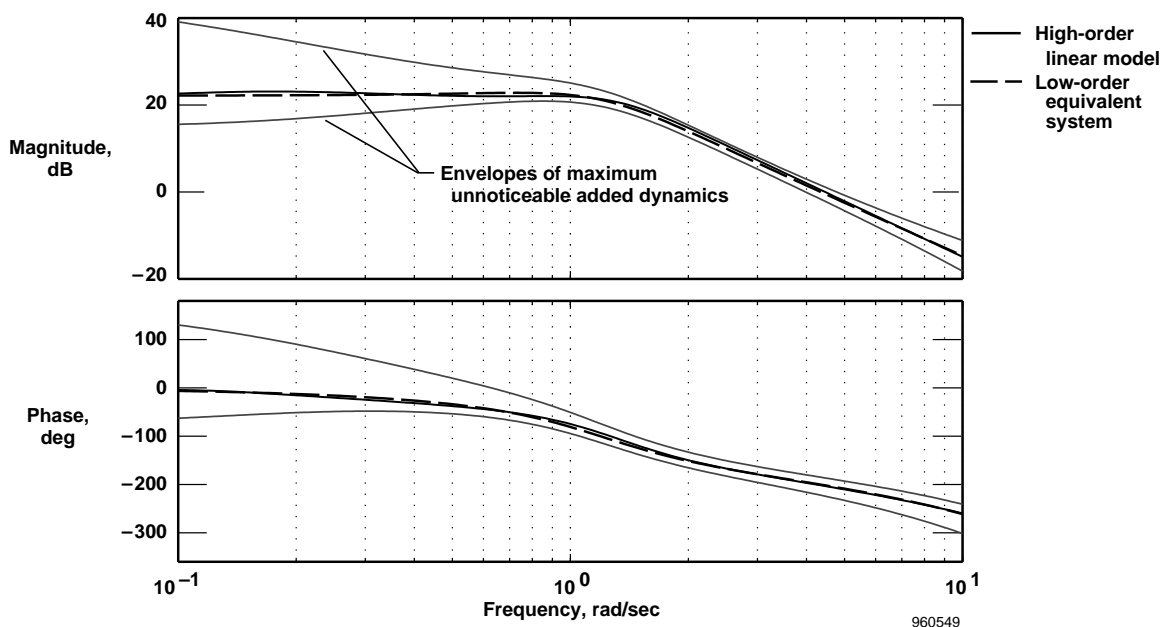


Figure 10. LOES as a function of high-order linear model pilot stick-to- α frequency response comparison for Version 28 at 30° α .

favorably. This transfer function was sufficient to provide the necessary parameters (short-period frequency and damping) for this criterion.

Figure 11 shows a sample comparison result of the predicted handling qualities for three flight control law versions. The short-period frequency of the criteria boundaries is scaled to 200 knots equivalent airspeed (KEAS) and 100 KEAS for acquisition and tracking, respectively, before plotting. Predictions for longitudinal tracking and acquisition at $30^\circ \alpha$ are plotted with the corresponding Cooper-Harper rating (CHR) from flight test in parentheses. Ratings of 1–3 correspond to Level 1 handling qualities; CHRs of 4–6 correspond to Level 2; and CHRs of 7–9 correspond to Level 3. No Version 26 gross acquisition performed in flight existed, so this point is not shown.

The gross-acquisition predictions indicate very similar characteristics with, at best, a median Level 2 rating. The flight results also reflect similar acquisition characteristics between the versions, but the overall level is nearer to Level 1 handling qualities than the predictions.

The tracking criterion reflects the trends observed in flight fairly well; Version 27 was significantly worse than the other two versions, and Version 28 exhibited the best qualities of the three. The Version 26 prediction was Level 2 as opposed to the CHR of 3 received in flight. All three versions received comments of varying levels of pitch-bobble sensitivity in tracking and acquisition. The guidelines predict similar pilot comments based on the location of the analysis values.

The lateral-directional axis of the ANSER control law was designed using the modal representation of these guidelines.¹² Figure 12 shows a comparison of the closed-loop linear design as a function of the MDA modal flying qualities criteria for 1-g design conditions at several angles of

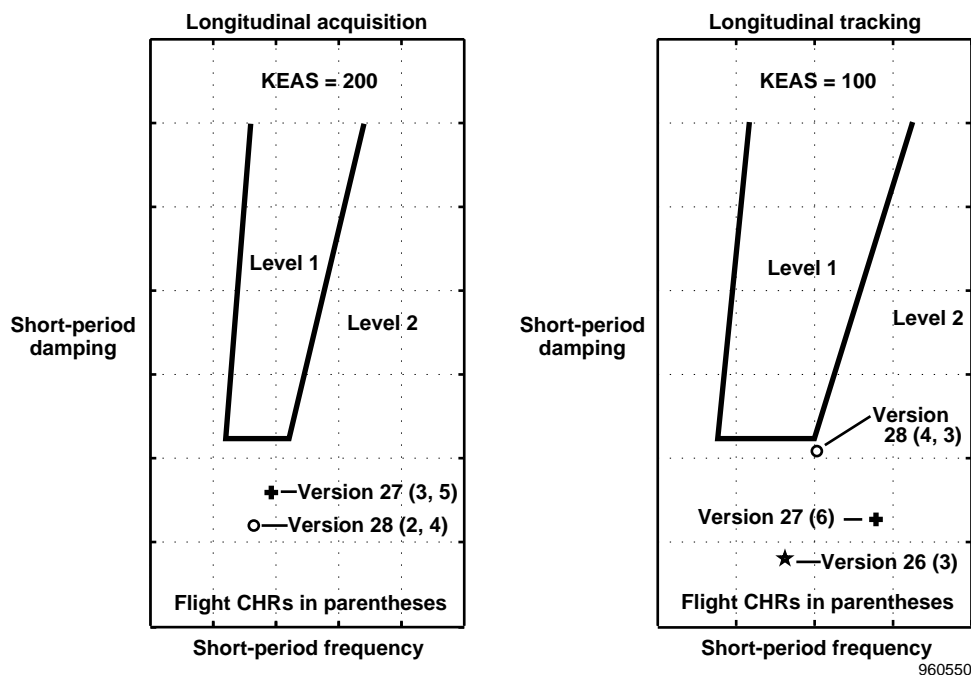


Figure 11. MDA longitudinal modal tracking criteria for $30^\circ \alpha$ with Versions 26, 27, and 28 linear predictions and actual pilot ratings.

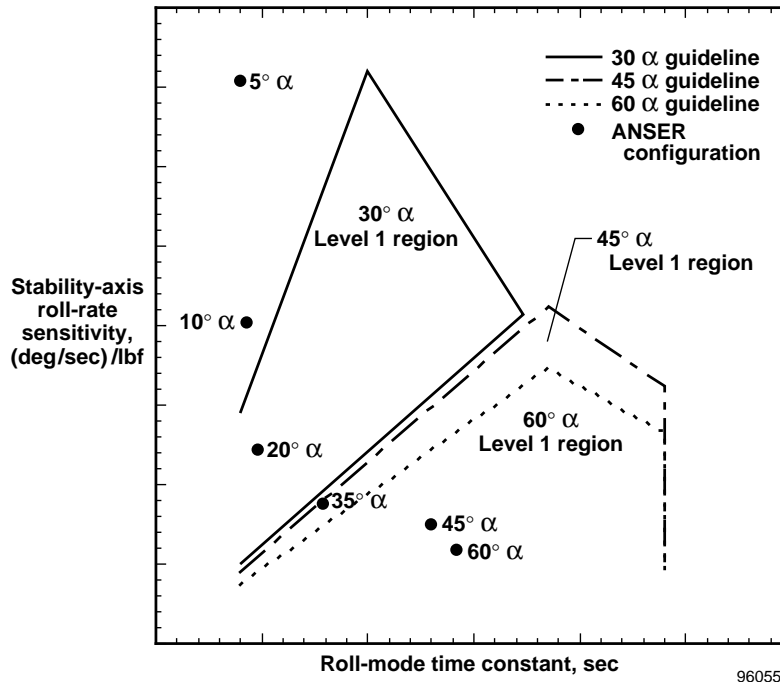


Figure 12. MDA lateral modal tracking criteria for 30°, 45°, and 60° α with ANSER linear design conditions.

attack. This figure shows the high- α criterion for lateral tracking in terms of closed-loop roll mode time constant as a function of stability-axis roll-rate sensitivity for the ANSER design. The region depicted by the solid line is the Cooper-Harper Level 1 region for 30° α , the region depicted by the dashed line represents the Cooper-Harper Level 1 region for 45° α , and the region depicted by the dotted line represents the Cooper-Harper Level 1 region for 60° α . In general, the closed-loop design points follow the trend of Level 1 flying qualities as a function of α according to MDA criteria.

The lateral-directional tracking tasks were flown by four pilots at 30° α , by five pilots at 45° α , and by two pilots at 60° α . At 30° α , the ratings were mostly Level 1. At 45° α , the ratings were mostly borderline Level 1–2. The average CHR at 30° and 45° α was 3.5 and 4.4, respectively. At these angles of attack, desired criteria were met by all but one pilot, who rated the dynamics significantly worse than the other pilots did. At 60° α , the average CHR was 7. Flying qualities were degraded at 60° α which, based on the pilot comments and flight data analysis, was most likely because of control power limitations. More overall comments on the applicability of the MDA modal criteria are given at the end of the MDA Bode criteria section.

McDonnell Douglas Aerospace–Proposed High-Angle-of-Attack Handling Qualities Criteria: Bode Guidelines

Level 1 Bode guidelines have been developed for both tracking and acquisition at 30° α and for poststall flight for the full-order pilot stick-to- α transfer function. The discussion in this paper is for α command systems, although the reference also includes guidelines for rate command systems.¹¹

As in the modal guidelines, the Level 1 boundaries for the Bode formulation are a function of flight condition. Guidelines are different for tracking and acquisition, and the 30° - α guidelines must be scaled with airspeed. In figure 13, the thick solid lines show the 30° - α tracking guidelines for two Mach numbers corresponding to longitudinal design data shown by the solid and dashed lines. (These criteria require the boundaries to be scaled in frequency by the ratio of velocity in *KEAS* to a standard of 140 *KEAS*. In order to overplot these two cases, the frequency of the data was scaled by the inverse of this ratio rather than scaling the boundaries.) These designs were made at 35° - α flight conditions. The 1-g case shows that the magnitude is greater than the upper boundary at high frequencies. The Mach 0.6 magnitude at a 4.5-g load factor remains within the Level 1 boundary for all frequencies. (The Mach 0.4 magnitude at a 2-g load factor results fell between these two cases.) The phase angle remains within the Level 1 boundaries for all cases.

Several pilots flew the 30° - α tracking maneuver, and varying degrees of sensitivity were experienced depending upon the pilot and technique used.¹³ Also, the high-speed flight tracking cases that were flown at approximately 20° α were less sensitive than the low-speed cases.

Although both the MDA modal and Bode criteria often predicted handling qualities indicative of those observed in flight, this was not always the case. The Bode criteria, although useful for engineering design, did not give good resolution in the discrimination of the observed tracking qualities differences for the NASA-0 control laws (Versions 26, 27, and 28) (fig. 14). Identifying definitive trends predicted among the versions is difficult. The Bode criteria tended to give more pessimistic predictions for 2-g and 3-g normal acceleration cases with this control law.

A few application observations can be made.

1. The MDA simulation study indicated that the desired dynamics are dependent on the task (gross acquisition or fine tracking). The boundaries for Level 1 tracking are different than those for acquisition at the same α . Because the Level 1 regions for the two tasks do not overlap, the control system designer must choose the best compromise between the Level 1 regions or tailor the control system (short-period frequency and damping) for the separate tasks to be flown at the same flight condition.
2. Applying the modal form of the criteria requires the design to be adequately represented by a LOES model that may be difficult to obtain from flight data for the high- α regime.
3. Applying these criteria requires a separate guideline for each α and for each task. Future research is needed to determine if critical “state” parameters of the handling qualities problem in the poststall region can be identified, thereby reducing the number of guidelines required.
4. These criteria were developed from fixed-based simulation data. Validation (or invalidation) of these guidelines through in-flight testing is still lacking.
5. For the modal formulation, an attempt to use linear representations of short-period frequency and damping for predicting gross-acquisition characteristics does not seem appropriate. These maneuvers are often flown with large pilot inputs and flight condition changes that result in significant nonlinearities.

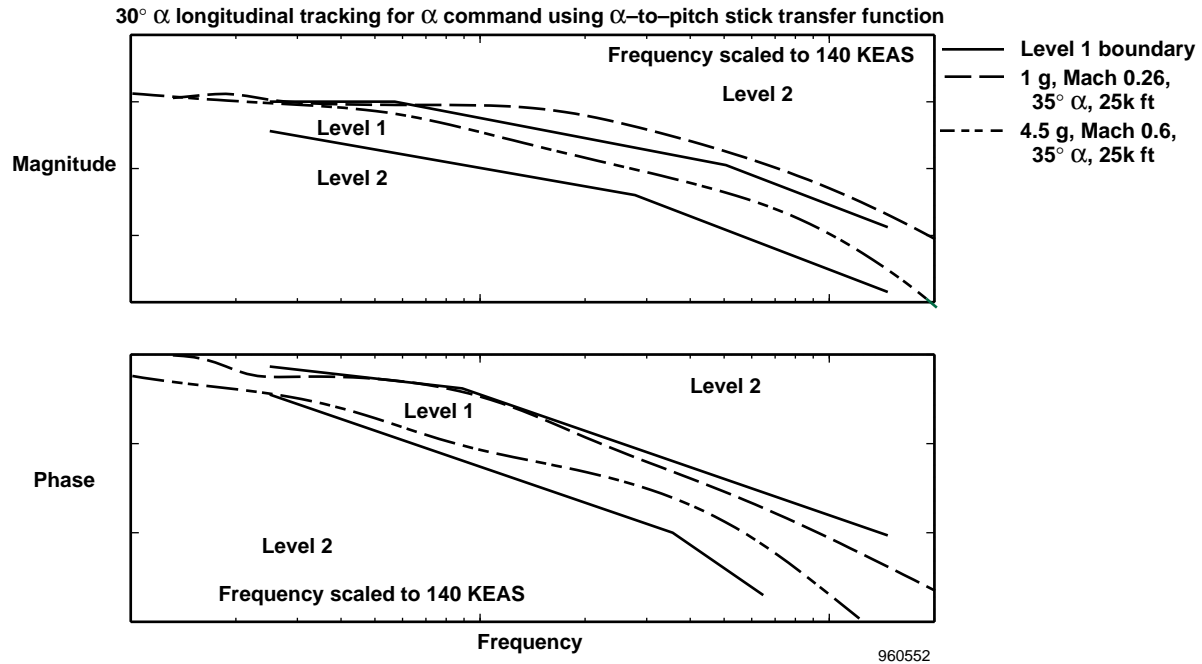


Figure 13. Bode tracking guidelines for angle-of-attack command with frequency response data from ANSER design at 35° α with Mach 0.26 (1 g) and Mach 0.6 (4.5 g).

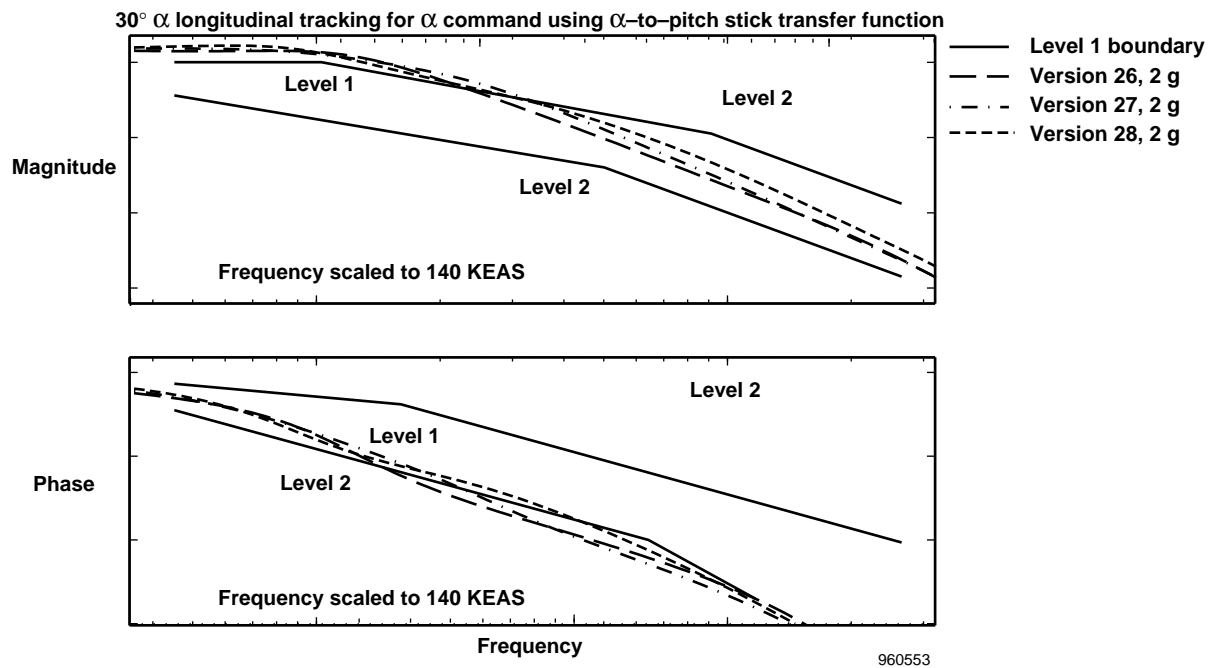


Figure 14. Bode tracking guidelines for 30° α with frequency response data from Versions 26, 27, and 28.

Low-Angle-of-Attack MIL-STD-1797 Criteria Extended to High Angle of Attack

Conventional low- α handling qualities criteria were evaluated for possible extension to the high- α flight regime. These linear techniques were tested for their ability to adequately predict flying qualities trends and levels observed in flight. The traditional boundaries were used by default but were not considered to be necessarily appropriate for the high angles of attack. The adjustment of these boundaries for high- α application was recognized as a potential outcome depending on the comparison with flight results.

Lower-Order Equivalent Systems–Based Criteria

Several conventional criteria require LOES transfer function representations of the full-order dynamics. Longitudinal LOES-based criteria that depend upon the time constant of the lag between flight path and pitch attitude ($T_{\theta 2}$) and the n/α were found to be particularly problematic at high α . These criteria include the control anticipation parameter (CAP); short period frequency, ω_{sp} as a function of n/α ; and $\omega_{sp}T_{\theta 2}$ as a function of short period damping, ζ_{sp} . The CAP is defined as:

$$\text{CAP} = \omega_{sp}^2 / (n/\alpha)$$

Because the lift-curve slope and, therefore, n/α become essentially 0 g/rad at high angles of attack, these criteria become meaningless. Figure 15 shows the general migration of predicted handling qualities with α using the CAP criterion as an example. As α increases, the value of the CAP approaches infinity. These conventional handling qualities criteria are based on the assumption that $1/T_{\theta 2}$ is approximately equivalent to the lift-curve parameter, which is appropriate for unaugmented aircraft. This assumption seems inappropriate when addressing highly augmented vehicles because these parameters are not designed to be similar. Such criteria were abandoned for further consideration in this study.

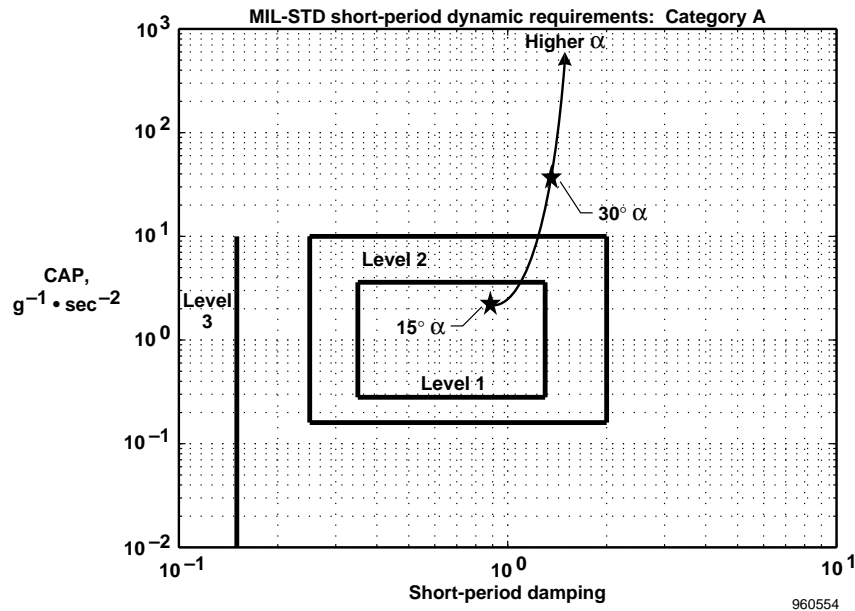


Figure 15. Migration of CAP criterion predictions with increased α .

Neal-Smith Criterion

The Neal-Smith criterion, which is also included in MIL-STD-1797, was examined in detail for application to high angles of attack.¹⁰ This criterion was developed using a database produced by the Calspan Corporation (Buffalo, New York).¹⁴ The criterion assumes a longitudinal tracking task with loop closure around a compensator of predefined form, an airframe, and flight control system dynamics. The compensator model is of the form

$$k_p e^{-\tau_{pilot}s} \frac{(T_{lead} s + 1)}{(T_{lag} s + 1)}$$

and closes the pitch attitude-to-pilot stick transfer function.

Figure 16 shows the Neal-Smith predictions for the NASA-0 three-version history previously described for tracking at $30^\circ \alpha$ using a bandwidth assumption of 3.0 rad/sec and compensator time delay of 0.3 sec. The bandwidth value was reduced from the recommended 3.5 rad/sec for this class of aircraft as a result of engineering judgment and simulation results implying that the task frequency requirements tend to decrease with increasing α . Overall HARV experience has indicated that these values were appropriate for correlation with flight results. Figure 16 also shows the variation with normal acceleration (1 g, 2 g, and 3 g) and the corresponding CHRs from flight test. (The flight conditions for these cases were between 2 g and 3 g.)

Predicted in the figure is a general improvement in the handling qualities as normal acceleration increases for each control law version. As mentioned earlier, the Version 27 flight test exhibited objectionable pitch bobble and sensitivity problems. From the pilot ratings and comments,

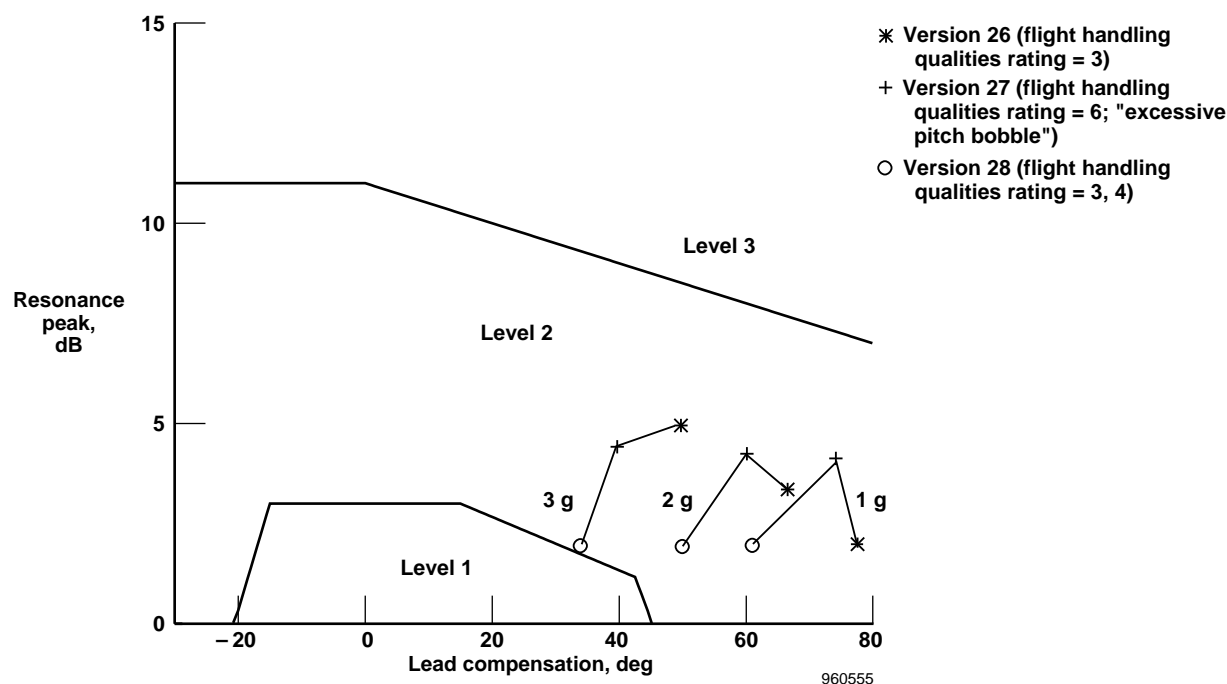


Figure 16. $30^\circ \alpha$ Neal-Smith results for Versions 26, 27, and 28 at 1 g, 2 g, and 3 g.

Version 28 appeared to give notably better handling qualities than either of the other versions. The predictions indicate the general trends observed in flight for the low- g cases. The 3- g case predicts Version 26 to be inferior to Version 27, as was the case with the MDA modal criteria. In all cases, Version 28 was predicted and observed to be superior to the other versions. Additionally, all versions were predicted to have Level 2 flying qualities, with the Version 28 results near the Level 1–2 boundary. Based on the flight results, one would expect the Version 27 level to be close to Level 3 and the Version 26 and 28 predictions to be close to the Level 1 region.

An important enhancement to the Neal-Smith criterion was the “carpet plot” representation (fig. 17). This representation was included to detect handling qualities “cliffs” where a severe degradation in flying qualities can occur for a configuration with changes in pilot gain or task bandwidth requirements.¹⁵ Figure 17 shows a family of Neal-Smith predictions for the Version 27 and Version 28 configurations but with variations in the bandwidth requirement and another task performance metric called “droop.” Thus, robustness to gain and phase variations can be depicted by such plots. The asterisk on the figure represents the nominal prediction (bandwidth = 3.0 rad/sec; droop = –3 dB). The bandwidth was varied by 0.5 rad/sec from 2.5 to 3.5 rad/sec. The droop ranged from 2.5 to 3.5 dB in increments of 0.5 dB. (The Version 28 carpet plot collapses to a line at 2 dB for the low-bandwidth cases.) Steep vertical slope and rapid traversing across the parameter plane indicate poor robustness, as can be seen in the Version 27 carpet plot. Here, the prediction is in the median Level 2 region, but a change of only 0.5 rad/sec in bandwidth moves it far into Level 3 flying qualities. Comparatively, the Version 28 predictions do not move as far with each increment, and their movement tends to be horizontal, indicating good handling qualities robustness.

This “third-dimension” view of the Neal-Smith criterion greatly enhanced its applicability and usefulness. It is important to have insight not only into the predicted nominal result, but also into

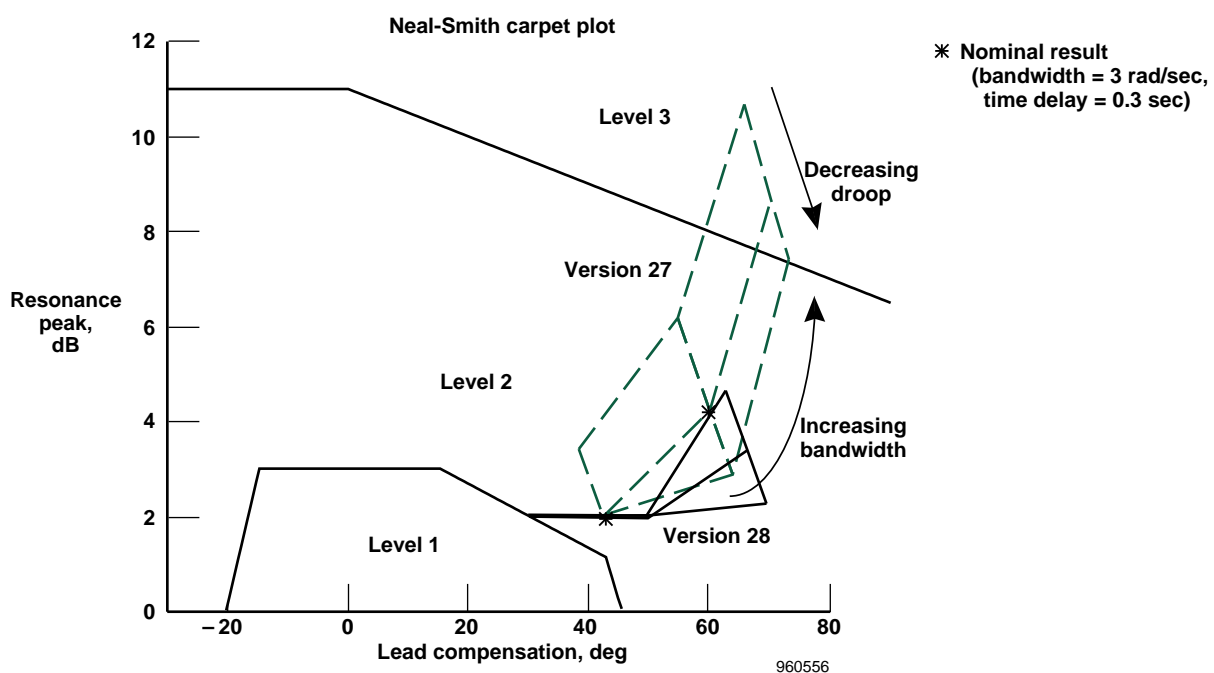


Figure 17. Neal-Smith “carpet plots” results for Versions 27 and 28 at 2 g and $30^\circ \alpha$.

how static that answer is in the presence of task and pilot variations. The carpet-plot analysis dramatically reflected the actual results obtained in flight. Version 28 exhibited reliably good tracking handling qualities. Version 27 could produce good handling qualities as the pilot backed out of the loop (low bandwidth), but this latter result was very sensitive to changes in pilot gain or task requirements.

Smith-Geddes Criteria

The Smith-Geddes criteria were designed to predict longitudinal and lateral-directional PIO susceptibility.¹⁶ As in the Neal-Smith criterion, the longitudinal criterion examines the pitch attitude-to-pitch stick transfer function in the frequency domain but with no assumption of a compensator outer-loop closure. The slope in the 1–6 rad/sec band is examined to determine the critical frequency,

$$\omega_c = 6.0 + 0.24 * (\text{slope in dB/octave})$$

The phase angle of the transfer function at this critical frequency is related to average CHR_s (fig. 18). Figure 18 shows the results for a normal acceleration of 2 g for the NASA-0 control laws (Versions 26, 27, and 28). The same comparative trends between the versions are evident; however, the overall predicted levels worsen (by approximately 1–2 CHR_s) when compared to the Neal-Smith predictions and the actual flight results. Versions 26 and 27 are predicted to be very near the Level 2–3 boundary, and Version 28 is predicted to be an improvement but only to the middle of the Level 2 region. The flight-observed CHR_s (also shown in the figure) for these versions were generally more favorable. No serious effort has yet been put forth to adjust the criteria for the high- α flight regime. The simulator studies used to produce the high- α modal and Bode criteria

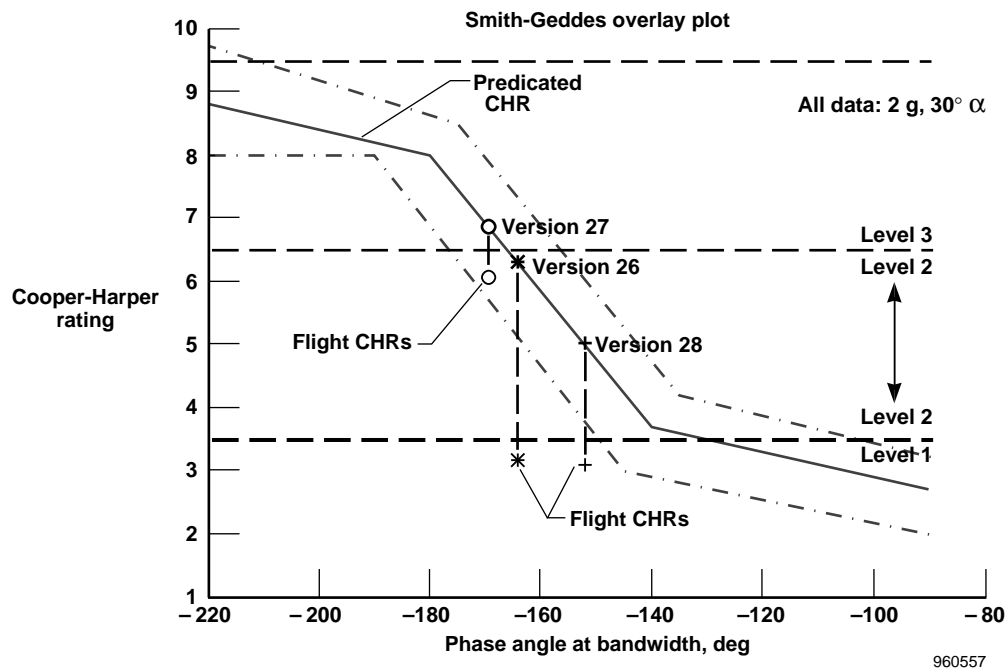


Figure 18. Smith-Geddes criterion predictions for Versions 26, 27, and 28 at 2 g and 30° α .

presented earlier pointed to a decrease in bandwidth requirement as the α increased. This decrease would tend to force the predictions to have better correlation with the flight results. More research and analysis is needed to place these boundaries more definitively.

Bandwidth Criterion

Another conventional longitudinal tracking criterion included in MIL-STD-1797 is the bandwidth as a function of time delay criterion.¹⁰ Pitch attitude-to-pilot stick transfer function frequency responses are used to determine the bandwidth frequency. The effective-time delay parameter is computed from the phase angle at twice the 180° phase crossover frequency and is plotted as a function of the bandwidth frequency for the conventional envelope (fig. 19).

Figure 19 shows the bandwidth criterion predictions for the NASA-0 control law versions (Versions 26, 27, and 28) for 1 g, 2 g, and 3 g. The same general improvement of handling qualities predictions with increased normal acceleration exists as in the Neal-Smith case. Additionally, the same trend among the versions exists, with Version 28 consistently predicted to be more favorable than the other two versions. The overall handling qualities predictions show a close grouping near the poor side of the Level 2 region with the most favorable prediction (Version 28, 3 g) being in the middle of this region. Like in the Smith-Geddes example, these results do not reflect the overall flying qualities levels exhibited by these versions in flight. Additionally, the flight test indicated much stronger discrimination between the sensitivity of Version 27 and the redesigned Version 28 configurations than is indicated by the bandwidth criterion predictions. Perhaps, as in the Smith-Geddes case, this discrepancy points to a potential requirement to adapt the boundaries of the level regions for the high- α flight regime. Reducing the required bandwidth frequency would shift the level regions to the left as indicated in the figure, improving the overall predicted levels. More research and analysis is needed to adequately determine what adaptation, if any, is required. Still, the criterion reflected the trends among versions observed during flight test.

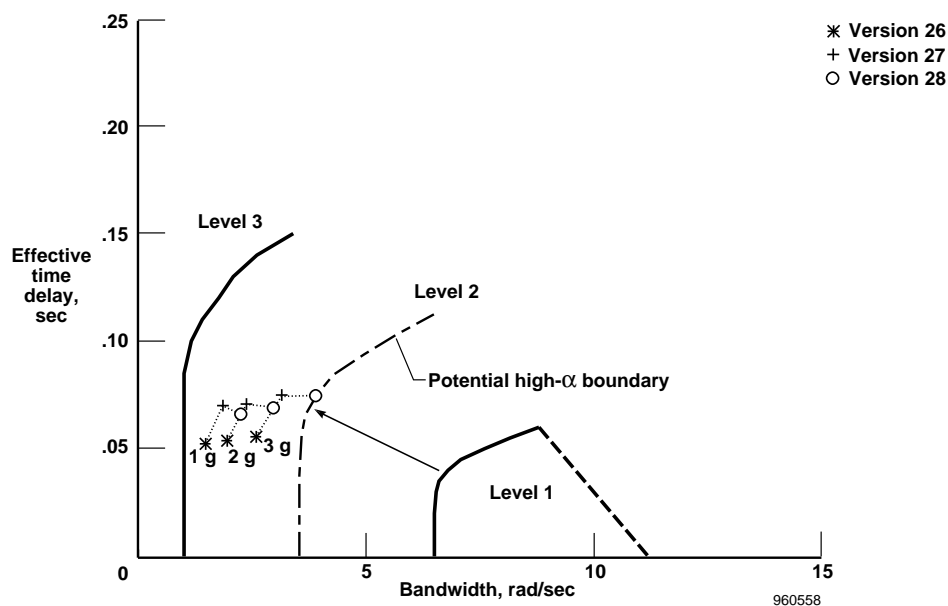


Figure 19. Bandwidth criterion predictions for Versions 26, 27, and 28 at 2 g and 30° α with possible adjusted high- α boundary.

Nonlinearity Compensating Techniques

Handling qualities criteria that include various levels of system nonlinearities were also evaluated. These criteria are discussed in the following sections.

Nonlinear Describing Functions and Limit-Cycle Analysis

Because of a severe episode of PIO encountered early in the flight test of the NASA-1A control law and a resolve that this should not happen again with the ANSER design, work was initiated in assessing the state of the art in predicting PIO susceptibility at high- α flight. To make this assessment, the “predictions” (made after flight test) for the NASA-1A control law were used in conjunction with the predictions for the ANSER control law and the subsequent flight results. A detailed summary of this research is given by Bacon.¹⁷ In brief, two strategies were employed to predict PIO susceptibility:

- Various linear PIO criteria were applied, incorporating describing functions to handle nonlinear effects (for example, actuator rate saturation).
- Multivariable limit-cycle approach was coupled with various pilot models, both linear and nonlinear, to uncover potential full-blown PIO tendencies.¹⁸

The linear procedures considered include the Neal-Smith criterion,¹⁴ the Smith-Geddes criteria,¹⁹ and the bandwidth criterion²⁰ described earlier in this paper. The rate saturation element of the stabilator actuator is replaced by a describing function that is a gain between zero and unity.²¹ A locus of handling quality parameters, different for each method, is then generated as a function of commanded actuator rate from the changing pitch-attitude frequency response. This nontraditional use of describing functions to ascertain limit-cycle or PIO potential of the pilot/vehicle system led to diagrams such as that shown in figure 20 depicting the effect on the Neal-Smith linear result for two flight conditions with the inclusion of these describing functions.

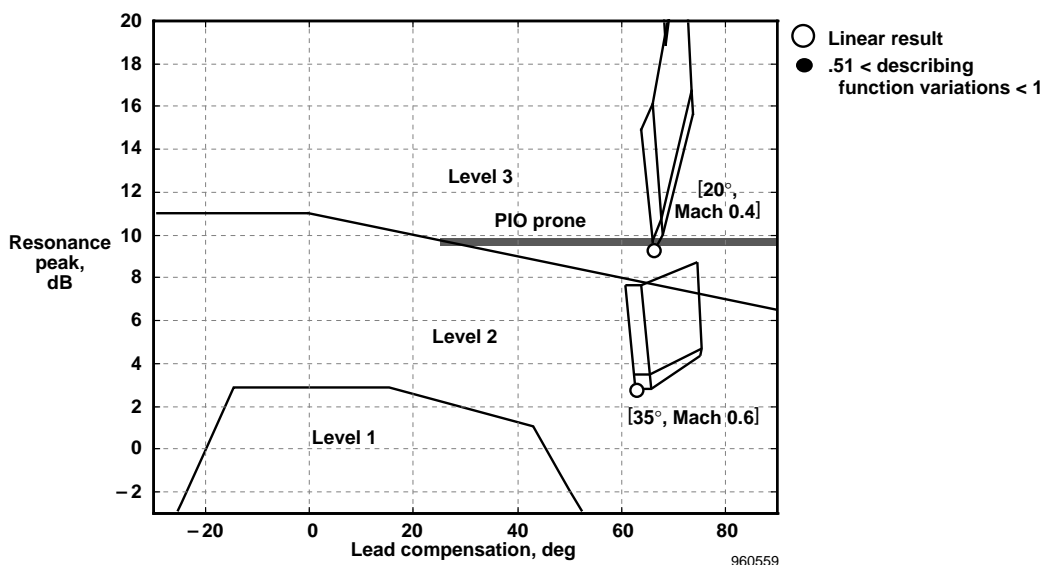


Figure 20. Quasilinear extension of Neal-Smith criterion with NASA-1A predictions for two flight conditions.

The multivariable limit-cycle approach used allows nonlinear behavior to be considered in both the vehicle and pilot. The approach combines structured singular-value methods, multivariable describing function methods, and pilot modeling to uncover potential PIO tendencies.¹⁸ Unlike Anderson's approach, a relay-switching model of the pilot is considered in addition to linear representations of the pilot. In the approach, structured singular values limit the search space, providing a necessary condition for solution, and also produce a likely pilot candidate for a set of uncertain pilot dynamics considered.

Although detailed results are given by Bacon,¹⁷ some general results are summarized here. All linear methods and quasilinear extensions gave consistent results in predicting PIOs. For NASA-1A, the quasilinear extensions that accounted for rate saturation were necessary to predict PIOs because the linear analyses alone (without using the carpet-plot representation previously discussed) revealed no PIO tendencies. The quasilinear extensions, however, failed to predict the level of commanded actuator rate required to initiate a PIO episode. The actual commanded actuator rate was smaller than predicted. For the ANSER control law, the quasilinear extensions reflected the trend in observed sensitivity but failed to predict the nuisance oscillations (bobbles) experienced in flight. To complicate matters, not all of the pilots experienced the nuisance oscillations using the ANSER control law. It became apparent that the collective test pilots' strategy used in uncovering PIO susceptibility was not covered adequately by the linear or quasilinear extensions. The second approach, which more accurately considers the effect of multiple nonlinearities as well as the uncertain dynamics of the pilot, was used to address the limitations of the first.

Proposed Time-Domain Neal-Smith Criterion

The conventional frequency-domain Neal-Smith criterion previously discussed has been reformulated in the time-domain by Calspan Corporation under contract to the U.S. Air Force.²² The same compensator is retained in the form

$$k_p e^{-\tau_{pilot}s} \frac{(T_{lead} s + 1)}{(T_{lag} s + 1)}$$

This compensator model is embedded into the nonlinear simulation of the subject aircraft, closing the loop around the full-order nonlinear control system, actuator models, and aerodynamics. The required task is to respond to a step error of 5° pitch attitude within a required acquisition time, D . An optimization loop is wrapped around this configuration to find the gain, k_p and compensation, T_{lead} and T_{lag} such that the root mean square (RMS) error between the response and the target pitch attitude is minimized after D . The resulting RMS error is plotted as a function of the phase angle at the bandwidth frequency on the time-domain Neal-Smith parameter plane where handling qualities regions are drawn.

The example time history (fig. 21) shows the optimized result for the HARV Version 28 configuration at approximately $27^\circ \alpha$ using an acquisition time of 1.5 sec. The resulting RMS error was approximately 0.2, and the phase angle at the bandwidth frequency was 64.2° . Figure 22 shows this result, along with those using a D of 1.3 and 1.7 sec, in order to estimate the robustness of this result to variations in bandwidth. The tracking handling qualities for this configuration in flight were observed to be near the Level 1–2 boundary as the prediction indicates. Additionally, this

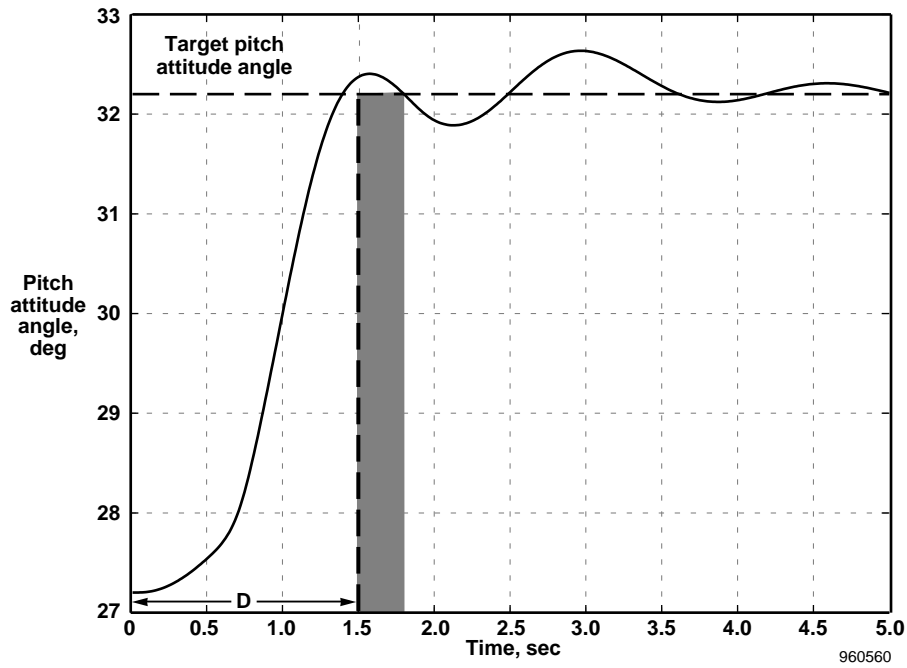


Figure 21. Time-domain Neal-Smith constrained pitch-attitude response with Version 28 at 27° α optimized time history.

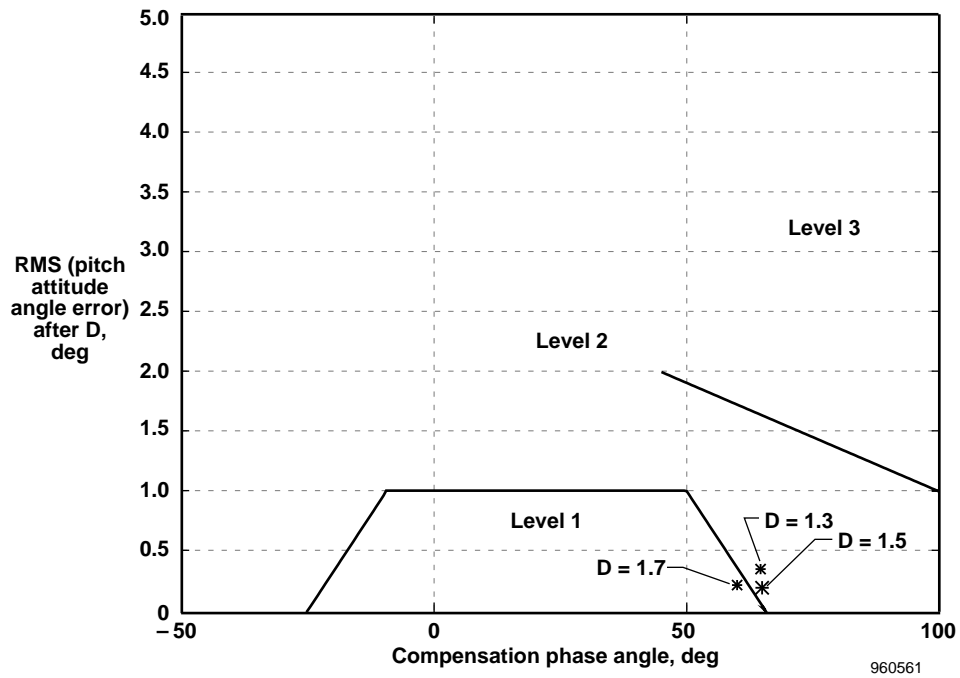


Figure 22. Time-domain Neal-Smith robustness predictions for Version 28 with variations in required acquisition time.

configuration exhibited good robustness to variations in task and pilot gain as is predicted by the very little migration of the prediction as the acquisition time is changed.

The potential benefits of this criterion to the high- α flight regime were recognized. The inherent inclusion of system nonlinearities and full-order dynamics is attractive, especially at high angles of attack. Additionally, the time required on condition is approximately 5 sec, whereas in order to generate a linearized frequency response from the nonlinear simulation using a frequency sweep input and Fast Fourier Transform analysis, more than 50 sec are required to produce meaningful results. For high- α flight, altitude is lost at a dramatic rate, resulting in large changes in flight condition from the beginning to the end of the maneuver. Thus, the short maneuver time required for this analysis technique is an important benefit. One drawback of the criterion is the very long optimization time required for each case because the simulation needs to be trimmed and operated for 5 sec, and the optimization code selects a new variable set, for each iteration.

Some modifications were introduced for adaptation to the HARV high- α problem. Most noteworthy was the addition of an integrator path in the pilot model necessitated by the α command control used at high angles of attack. Additionally, the nominal D , which is the time-domain equivalent to bandwidth in the frequency domain, was increased from that of the low- α formulation. This increase was done based on engineering judgment and experience with other criteria adaptation to high angles of attack. Final recommendations for D in this criterion for high α require further study. It should be noted that this work has not been finalized and the criterion cannot be considered validated for high- α application as of yet. The results, however, have been promising. Additionally, no obvious reason exists why this technique could not be applied to the lateral axis as well.

HIGH-ANGLE-OF-ATTACK HANDLING QUALITIES DATABASE

The archival of the HARV high- α handling qualities raw information into a usable database was an objective of the HARV handling qualities research. Several components make up the HARV database:

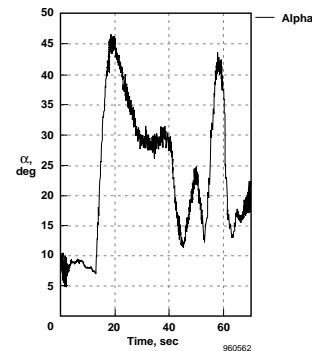
- Linear models of all control law versions.
- Nonlinear six-degrees-of-freedom simulations.
- Piloted simulation handling qualities database for baseline flight comparison.
- Pilot ratings and comments (transcribed and digitized audio) from flight.
- Pilot ratings and comments from dome simulations.
- HUD or glareshield video for each flight maneuver.
- Flight data in engineering units.

Figure 23 shows a sample HARV handling qualities comment card transcribed from the digitized audio. This database is currently in the process of being archived in a form useful for future analysts. This database should help engineers to further develop and evaluate criteria, plan flight programs, and add to the database where it is lacking. An important by-product of this handling qualities research has been the production of a MATLAB® (The MathWorks, Inc., Natick, Massachusetts) handling qualities toolbox of analysis routines. All of the examples given in this paper were produced using these tools developed by the NASA team.

HARV HQ Comment Card

Flight: 319
Card #: 12A
CLAW: 151.1
Mode: TV
Gain Set: Medium
Pilot: Schneider
Target A/C: 850/Smolka
Mach No: 0.45
Altitude: 25000.
Target AOA: varies
Maneuver: .45M Tracking
Actual AOA: 11-46 (30 avg.)
Reticle/Depression: 12.5/80mil
Desired: within 5mil 50% time and within 25mil remainder
Adequate: within 5mil 10% time and within 25mil remainder
Date: 07Sept95

HARV flight 319 card 12A
.45 Mach Longitudinal/Lateral Tracking TV



File=flt319.12a; Signal Suffix=[none]; Date=[none]

Pilot Comments: Maneuver,... Burner,... ok, on him... a little longitudinal bobble, 32 alpha... nose... right wing... left wing. Kind of a helico-[Controller] Reverse. [Pilot] nose... reverse, good... see the pitch bobble? [Controller] Reverse. [Pilot] here comes the reverse... [Controller] Reverse. ... and recover, altitude. [Pilot] OK, knock it off. [Target] Knocking it off. [Pilot] Very good.
(snip to post-maneuver comments)

Attitude Control:

Undesirable Motion: OK, comments; undesirable motions; the only one that I really did not like was the longitudinal pitch bobble that we've seen before on other tracking tasks. And it's still there, probably due to the major dumbbell effect that we have with the airplane.

Predictability: Predictability was pretty good, except in the long axis. You could sometimes over-control pretty easily there and get the pipper off from where you wanted it.

Initial Response: Initial response was good in both axes.

Aggressiveness Effects H/Q: Aggressiveness had a major effect on the longitudinal pitch bobble. If you really got on it it wasn't... wasn't gonna settle down. And you had to compensate with... being a little more open hand, little bit less aggressive with the controls in that axis. And... trying to... separate out the lateral control movements from the longitudinal. That's a little bit aggravating too when you go from wingtip to wingtip.

Compensation Techniques:

Roll Performance: Roll performance, I thought was quite good.

RPC:

Feel System:

Forces: And ... forces were light, satisfactory.

Control Motion: Control motions; small.

Harmony: Harmony was good.

Nonlinearly: It was linear.

Cooper Harper Rating:

Longitudinal HQR: [4] Longitudinal first. Controllable? Yes. Adequate performance? Yes. Satisfactory without improvement? No.

Desired performance required moderate compensations. I'd give it a 4. I think I had desired performance there, but I definitely did not like the longitudinal bobble, and you can ask Keith to think about that for a minute and see if he agrees.

Lateral/Dir. HQR: [3] And for the lateral axis... Controllable? Yes. Adequate performance? Uh, yes. Satisfactory without improvement? I would say "yes". And I would say... minimal compensation in the lateral axis. HQR 3.

Confidence Rating: [1] And... confidence rating: I'd give it a 1 on that one.

PIO Rating:

Other Comments:

Times:	Target Maneuver:	11:11:18 (right turn)
	Maneuver:	11:11:21
	Acquisition:	11:11:28 (42° AOA)
	Knock It Off:	11:12:10
	Comments Begin:	11:12:31
	Comments End:	11:14:29

Figure 23. Sample HARV database pilot comment transcription.

RECOMMENDATIONS

Based on this research, the following recommendations for further investigation can be made:

- A dedicated high- α handling qualities investigation using a true variable-stability aircraft would greatly improve the understanding in this area. This investigation would allow greater variation in dynamics, especially in the lateral-directional axes, to more completely evaluate handling qualities criteria, including the placement of level boundaries for conventional criteria for this regime than the HARV handling qualities research program allowed.
- More detailed evaluation of the current data using lateral-directional criteria should be conducted.
- Direct comparison with X-31A handling qualities results should be performed and reported.
- The high- α pyramid maneuvers developed using the HARV aircraft should be seriously considered for adoption into any future high- α flight research program. The maneuvers can also improve efficiency of flight test by doubling as envelope expansion and research maneuvers simultaneously.
- Conventional, low- α handling qualities criteria (Neal-Smith, Smith-Geddes, and bandwidth) should also be seriously considered for application to high- α design. Boundary redefinition as suggested in this paper should be considered.
- Nonlinear techniques showed great promise and should be explored thoroughly, especially for application to high angles of attack where nonlinearities are prevalent.
- Piloted simulation handling qualities evaluation should be exploited but with caution. Often handling qualities deficiencies (especially PIO) are not readily uncovered from simulation. The “stepping target” simulation task can be very effective at exposing deficiencies before flight that might go unnoticed otherwise.

SUMMARY

A flight research study of high-angle-of-attack handling qualities was conducted at the NASA Dryden Flight Research Center in cooperation with the NASA Langley Research Center on the F/A-18 High Alpha Research Vehicle (HARV). The HARV aircraft, equipped with a reconfigurable research flight control system, multiaxis thrust-vectoring control system, and forebody vortex control using the actuated nose strakes for enhanced rolling system integrated into the stable high-angle-of-attack F/A-18 airframe, was an excellent facility for this investigation. The research objectives were to create a high-angle-of-attack handling qualities flight database, develop appropriate research evaluation maneuvers, and evaluate high-angle-of-attack handling qualities guidelines and criteria.

Maneuvers were developed and flight-validated for the evaluation of high-angle-of-attack handling qualities. Ground-based simulations were used extensively to develop and refine these maneuvers. Some in-flight trial and error was required to refine them. These maneuvers were very effective at discriminating handling qualities from 30° through 60° angle of attack.

Another major thrust of the HARV handling qualities research was the evaluation of techniques for predicting and specifying high-angle-of-attack handling qualities. Using linear and nonlinear simulations and flight research data, the results from each analysis technique were compared with the pilot ratings and comments from the flight evaluations. Considered in this study were proposed high-angle-of-attack nonlinear design guidelines developed by NASA Langley Research Center and proposed handling qualities criteria and guidelines developed using piloted simulation. Recently formulated time-domain Neal-Smith guidelines were also considered for application to high-angle-of-attack maneuvering. Conventional envelope criteria such as bandwidth, Neal-Smith, Smith-Geddes, and lower-order equivalent systems-based guidelines found in MIL-STD-1797 were evaluated for possible extension to the high-angle-of-attack regime. Additionally, the maneuvers themselves were examined as potential evaluation techniques and guidelines including a limited validation of the proposed standard evaluation maneuvers set.

Results to date suggest that the traditional linear techniques can be effectively extended to this flight regime in spite of the increase in nonlinearity associated with high-angle-of-attack flight. Assumptions of linearity appear appropriate, provided the evaluation is limited to relatively small perturbations about a quasisteady-state condition. Thus, handling during coarse- and fine-tracking maneuvers could generally be predicted using linear techniques such as the Neal-Smith, Smith-Geddes, and bandwidth criteria. Maneuvers requiring large inputs or resulting in great change of flight condition were sharply affected by nonlinearity such as control surface rate and position saturation. Nonlinear extensions to the linear techniques, such as describing functions and multivariable methods, as well as alternative guidelines were evaluated and found to be promising.

It was also shown that for this flight regime, criteria or guidelines requiring lower-order equivalent systems evaluation were particularly problematic. Included in this category were military standard handling qualities criteria and proposed high-angle-of-attack modal handling qualities criteria. Another set of proposed guidelines that were framed in terms of transfer function boundaries in the frequency domain was also evaluated. However, an attempt to predict gross-acquisition characteristics where nonlinearity likely abounds because of large inputs and flight condition changes was not considered appropriate using a linear frequency response representation.

The research experiment conducted using the HARV aircraft resulted in a comprehensive yet limited handling qualities flight database for the high-angle-of-attack flight regime where none previously existed, and important insights can be derived from it. The study evaluated longitudinal and lateral-directional gross-acquisition and tracking handling qualities from 30° through 60° angle of attack. Numerous control law configurations and advanced control effectors, including the forebody strakes and thrust vectoring, were used to vary both available control power and the closed-loop dynamics. The handling qualities of these configuration variations ranged from excellent tracking and gross-acquisition characteristics to very poor handling qualities, including sustained pilot-induced oscillations. An extensive simulation database using fixed-base dome and some motion-based simulation was created for comparison with flight results. Head-up display video and pilot comments were cataloged with the flight time-history data. An important by-product of this handling qualities research has been the production of a MATLAB® handling qualities toolbox of analysis routines. All of the examples given in this paper were produced using these tools developed by the NASA team.

REFERENCES

- ¹Stoliker, P. C. and Bosworth, John T., *Evaluation of High-Angle-of-Attack Flying Qualities for the X-31A Using Standard Evaluation Maneuvers*, NASA TM-104322, Sept. 1996.
- ²Kidman, David S., Vickers, Jesse E., Olson, Brian P., and Gerzanics, Michael A., *Evaluation of the F-16 MultiAxis Thrust Vectoring Aircraft*, AFFTC-TR-95-12, Sept. 1995.
- ³Bowers, Albion H., Pahle, Joseph W., Flick, Bradley C., and Rood, Richard L., "An Overview of the NASA F-18 High Alpha Research Vehicle," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.
- ⁴Hoffler, Keith D., Brown, Philip W., Phillips, Michael R., Rivers, Robert A., Davidson, John B., Lallman, Frederick J., Murphy, Patrick C., and Ostroff, Aaron J., "Evaluation Maneuver and Guideline Development for High-Alpha Control Law Design Using Piloted Simulation," AIAA-94-3512-CP, Aug. 1994, pp. 435-448.
- ⁵Pahle, Joseph W., Foster, John V., Bundick, W.T., and Wichman, Keith D., "An Overview of Controls and Flying Qualities Technology on the F/A-18 High Alpha Research Vehicle," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.
- ⁶Hoffler, Keith D., Messina, Michael D., and Wilson, Ronald J., "Flight Test and Piloted Simulation Assessment of Evaluation Maneuvers and Nonlinear Guidelines Developed for High-Alpha Control Law Design," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.
- ⁷Wilson, David J., Riley, David R., and Citurs, Kevin D., "Aircraft Maneuvers for the Evaluation of Flying Qualities and Agility," WL-TR-93-3081-3084, vol. 1-4, Aug. 1993.
- ⁸Klyde, David H., Citurs, Kevin D., and Mitchell, David G., "In-Flight Evaluation of the Standard Evaluation Maneuver Set (STEMS) with the NASA F/A-18 HARV," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.
- ⁹Hoffler, Keith D. and Carzoo, Susan W., "A Piloted Simulation Test Technique Developed to Reveal Pilot Induced Oscillation (PIO) Tendencies During Tracking Tasks," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.
- ¹⁰U.S. Department of Defense, *Flying Qualities of Piloted Vehicles*, MIL-STD-1797, Mar. 1987.
- ¹¹Wilson, David J. and Citurs, Kevin D., *High Angle of Attack Flying Qualities Design Guidelines*, NASA CR-4681, Feb. 1996.
- ¹²Murphy, Patrick C., Davidson, John B., Lallman, Frederick J., Morelli, Eugene A., Messina, Michael D., Connelly, Patrick J., and Thomson, Michael P., "An Evaluation of Design Methodology and High Alpha Design Criteria for the ANSER Lateral-Directional Control Law," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.
- ¹³Ostroff, Aaron J. and Wichman, Keith D., "Flight Evaluation of a Variable-Gain Output Feedback Longitudinal Control Law for the NASA F/A-18 High Alpha Research Vehicle (HARV)," *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.

¹⁴Neal, T. Peter and Smith, Rogers E., “An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes,” AFFDL-TR-70-74, vol. 1, Dec. 1970.

¹⁵Bailey, Randall E. and Smith, Rogers E., “Analysis of Augmented Aircraft Flying Qualities through Application of the Neal-Smith Criterion,” AIAA-81-1776, Aug. 1981.

¹⁶Smith, Ralph, “The Smith-Geddes Criteria,” *SAE Aerospace, Control & Guidance Systems Symposium*, Reno, Nevada, Mar. 1993.

¹⁷Bacon, Barton J., “PIO Susceptibility of the F-18 HARV: Analysis/Prediction vs. Flight,” *High-Angle-of-Attack Technology Conference*, Hampton, Virginia, Sept. 1996.

¹⁸Anderson, Mark R. and Page, Anthony B., “Multivariable Analysis of Pilot-in-the-Loop Oscillation,” AIAA-95-3203-CP, Aug. 1995, pp. 278–287.

¹⁹Smith, Ralph H. and Geddes, Norman D., “Handling Quality Requirements for Advanced Aircraft Design: Longitudinal Mode,” AFFDL-TR-78-154, Aug. 1979.

²⁰Mitchell, David G. and Hoh, Roger H., “Development of a Unified Method to Predict Tendencies for Pilot-Induced Oscillations,” WL-TR-95-3049, June 1995.

²¹Adams, Richard J., Buffington, James M., and Banda, Siva S., “Active Vortex Flow Control for VISTA F-16 Envelope Expansion,” AIAA-94-3681, Aug. 1994, pp. 1259-1269.

²²Bailey, Randall E. and Bidlack, Timothy J., *Quantitative PIO Criterion Development - Time-Domain Neal-Smith Criterion*, Calspan Final Report no. 8184-12, Aug. 1995.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 1996		3. REPORT TYPE AND DATES COVERED Technical Memorandum
4. TITLE AND SUBTITLE High-Alpha Handling Qualities Flight Research on the NASA F/A-18 High Alpha Research Vehicle			5. FUNDING NUMBERS WU 505-68-30	
6. AUTHOR(S) Keith D. Wichman, Joseph W. Pahle, Catherine Bahm, John B. Davidson, Barton J. Bacon, Patrick C. Murphy, Aaron J. Ostroff, Keith D. Hoffler				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Dryden Flight Research Center P.O. Box 273 Edwards, California 93523-0273			8. PERFORMING ORGANIZATION REPORT NUMBER H-2138	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-4773	
11. SUPPLEMENTARY NOTES Presented at the NASA Langley High-Angle-of-Attack Conference, Langley Research Center, Sept. 17-19, 1996. Keith Wichman, NASA Dryden Flight Research Center, Edwards, California. Joseph Pahle, NASA Dryden Flight Research Center, Edwards, California				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified—Unlimited Subject Category 08			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A flight research study of high-angle-of-attack handling qualities has been conducted at the NASA Dryden Flight Research Center using the F/A-18 High Alpha Research Vehicle (HARV). The objectives were to create a high-angle-of-attack handling qualities flight database, develop appropriate research evaluation maneuvers, and evaluate high-angle-of-attack handling qualities guidelines and criteria. Using linear and nonlinear simulations and flight research data, the predictions from each criterion were compared with the pilot ratings and comments. Proposed high-angle-of-attack nonlinear design guidelines and proposed handling qualities criteria and guidelines developed using piloted simulation were considered. Recently formulated time-domain Neal-Smith guidelines were also considered for application to high-angle-of-attack maneuvering. Conventional envelope criteria were evaluated for possible extension to the high-angle-of-attack regime. Additionally, the maneuvers were studied as potential evaluation techniques, including a limited validation of the proposed standard evaluation maneuver set. This paper gives an overview of these research objectives through examples and summarizes result highlights. The maneuver development is described briefly, the criteria evaluation is emphasized with example results given, and a brief discussion of the database form and content is presented.				
14. SUBJECT TERMS Database, Criteria guidelines, Handling qualities, High-angle-of-attack, Maneuvers			15. NUMBER OF PAGES 38	
			16. PRICE CODE AO36	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	